

CCSDS - SFCG

EFFICIENT MODULATION METHODS STUDY

AT NASA/JPL

PHASE 4: INTERFERENCE SUSCEPTIBILITY

**Warren L. Martin
Tsun-Yee Yan
Andrew Gray
Dennis K. Lee**

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EFFICIENT MODULATION METHODS - INTERFERENCE SUSCEPTIBILITY

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1.0 INTRODUCTION

At its September 1998 meeting in Galveston, Texas, the Space Frequency Coordination Group (SFCG) adopted provisional Recommendation 17-2 dealing with *Efficient Spectrum Utilization for Space Science Services*. It did so following a five-year study by the Consultative Committee for Space Data Systems (CCSDS) which examined bandwidth efficiencies of modulation schemes which the Space Agencies were using or considering for use (References 1, 2, 3, 4 and 5). This study was begun in 1992 at the request of the SFCG and contributions were provided by: NASA's Jet Propulsion Laboratory (JPL), NASA's Goddard Space Flight Center (GSFC), European Space Agency's (ESA's) European Space Operations Center (ESOC), New Mexico State University, and the Aerospace Corporation. SFCG Provisional Recommendation 17-2 included a spectrum mask regulating unwanted RF emissions. Following a 1-year provisional status, SFCG-18 adopted Rec. 17-2R1 SFCG-18 (Reference 6). Recommendation 17-2R1 includes the spectrum mask shown in Figure 1.0-1 limiting emissions in the 2 and 8 GHz bands.

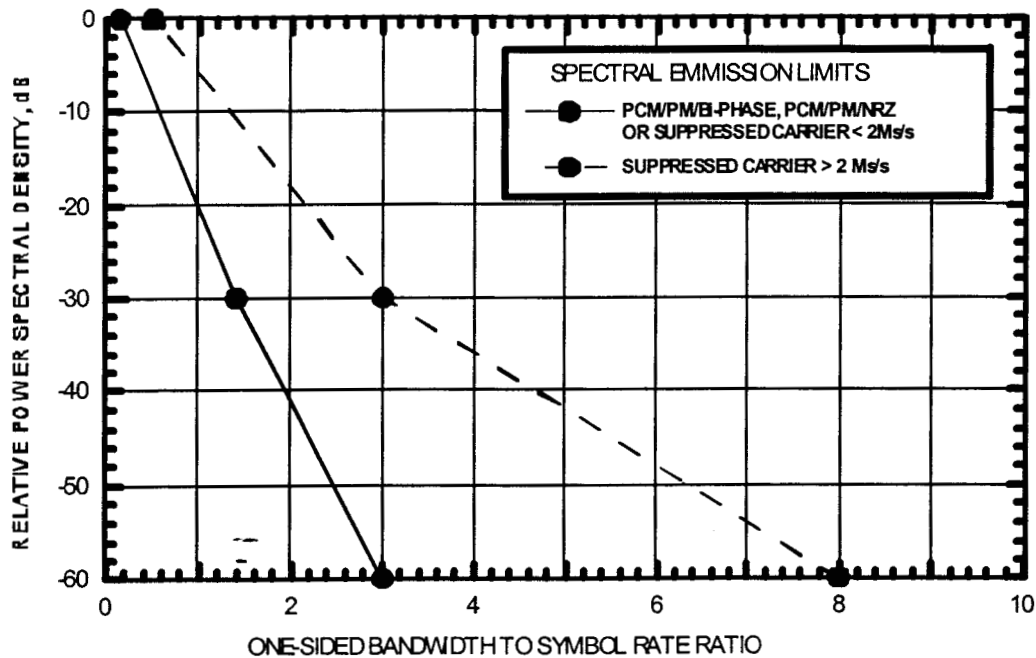


Figure 1.0-1: SFCG Spectrum Mask

This mask partitions missions into two types, those with telemetry data rates greater than 2 Mega symbols per second (Ms/s) and those with rates below 2 Ms/s. The former are constrained to use a suppressed carrier modulation while the latter are permitted to use either suppressed or residual carrier. Spacecraft telemetry systems for missions starting after 2001 should comply with the relevant mask. Some sort of filtering will be required to meet these masks. At SFCG-18, a question arose as to whether narrowing the RF spectral bandwidth will increase the susceptibility to interference. This Phase 4 Efficient Modulation Methods study seeks to determine if that is so.

EFFICIENT MODULATION METHODS - INTERFERENCE SUSCEPTIBILITY

Definition of Interference Susceptibility:

The likelihood that another signal source, operating in the same or other allocated frequency band, will produce an unacceptable degradation to a victim employing bandwidth efficient modulation.

Some SFCG-18 representatives speculated that narrowing the transmitted RF spectrum will increase a modulation type's interference susceptibility. Subsequent to the SFCG's action item, the following Workplan was devised:

"A18-17/2 Workplan: Interference Susceptibility of Bandwidth Efficient Modulation Schemes

The action item consists in determining which is the RFI [Radio Frequency Interference] level that will cause a degradation of 1 dB in link performances. The analysis will be done for two types of radio frequency interferences (RFI):

- *A pure carrier (narrow band case)*
- *A wide band RFI (TBD)*

both centred at the useful signal centre frequency and then at 0.5 x symbol rate from the centre frequency.

Modulations to be considered are:

Task 17/2-1: Unfiltered BPSK (benchmark)

Task 17/2-2: GMSK BT=0.5

Task 17/2-3: GMSK BT=1

Task 17/2-4: OQPSK filtered with a 6-pole Butterworth filter, BT=1

Task 17/2-5: OQPSK filtered with a SRRC filter, roll-off factor of 0.5

Task 17/2-6: FQPSK

In all cases, the transmitted signal is passed through a non-linear channel, TWTA with 0 dB backoff.

The report will provide AM/AM and AM/PM characteristics of the TWTA.

It must be noted that the actual performances in the presence of RFI are those of the receiver and may vary a lot with the chosen design. Therefore, the report will also include a description of those features in the receiver design which are influential in RFI susceptibility, e.g., carrier tracking loop, bit synchronizer."

Subsequent Workplan clarification revealed that a Solid State Power Amplifier, not a TWT, should be used in this evaluation. The same amplifier used in Reference 4 was selected for this study.

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2.0 STUDY DESCRIPTION

Susceptibility to two types of interfering signals was requested by the SFCG: a pure carrier (single frequency tone) and wide-band RFI (characteristics unspecified). Selecting a broad-band interfering signal is difficult because it should represent the types of interference to be found in the space science service bands. Given currently allocated services, such broad-band interference is likely to result from a digitally modulated signal, having a rate of a few megabits per second, and with a power level similar to the victim's. Moreover, the interferer is not likely to employ one of the bandwidth-efficient modulation methods permitting frequency assignments to be made with no spectral overlap between users in their *necessary bandwidths*. Accordingly, the broadband interferer is expected to be something like unfiltered Binary Phase Shift Keyed (BPSK) modulation. That modulation type was used as the broadband interferer for this Phase 4 study.

2.1 Study Approach

This study was based on a dual approach. First, a theoretical analysis was made to determine the modulation type's susceptibility to both narrowband and wideband interference. From this analysis, simulations generated curves showing losses to the victim's received signal resulting from an interferer as its frequency separation from the victim signal changes and its relative power to the victim varies. An analysis was made for each of the modulation types listed in the Workplan.

Where possible, theoretical simulations were verified by simulation of a hardware system. The hardware simulation's sole purpose was to validate the analytical computations by "spot-checking" several points, not to generate complete interference susceptibility curves. Hardware simulations of the Digital Signal Processor (DSP) employ Hardware Description Language (HDL), which has been validated using actual APRX receiver hardware.

2.1.1 Transmitting System

Spectra for the several modulation methods appear in the *CCSDS-SFCG Efficient Modulation Methods Study Phase 3* report (Reference 4). In completing this interference susceptibility analysis, it was desirable to retain the compact spectra measured during that study in order to comply with the spectrum mask contained in SFCG Recommendation 17-2R1. Therefore, an attempt was made to use the same, constant envelope, transmitting system employed in Phase 3.

Phase 3 studies demonstrated that the *Universal Phase Modulator* did well in generating QPSK but poorly with OQPSK. QPSK is not specified in the Workplan and most of the modulation methods identified (OQPSK, GMSK, and FQPSK) require an OQPSK modulator. In Phase 3 it was found that a linear phase modulator, with baseband filtering, produced discrete components within the comparatively narrow RF spectrum. Conversely, baseband filtering with an In-Phase-Quadrature (I-Q) modulator significantly reduced spectral spikes but produced a large amount of Amplitude Modulation (AM) widening the transmitted RF spectrum. Nevertheless, an I-Q phase modulator was determined to be the better choice for Phase 4 (see Section 3.2.1).

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2.1.1.1 Baseband Filtering

Phase 3 studies concluded that Intermediate Frequency (i.f.) and post power amplifier filtering were impractical for several reasons and such filtering will not be considered further here (Reference 4). There is also a change in the Square Root Raised Cosine (SRRC) filter's design. Phase 3 simulations assumed a spacecraft data system producing an NRZ signal feeding a device approximating an SRRC waveform. This mechanization was selected because the original SFCG study guidelines called for minimum changes to the spacecraft's hardware, mandating an NRZ data source.

A proper system generates an impulse which passes through an SRRC filter producing a true SRRC waveform. While yielding significantly better performance, this method also requires modifications to spacecraft's data system hardware. Since the Efficient Modulation Methods Study was first begun in the early 1990s, attitudes have changed and hardware modifications are now acceptable. Therefore, this study generates an SRRC filter in the proper manner, significantly improving the system's performance.

2.1.2 Interfering Signal Types

Figure 2.1-1 graphically depicts the different interference types. Consider an FQPSK-B telemetry signal having a spectrum centered at f_c and a width of about $\pm 1 R_b$ at 60 dB below its peak level. The victim's receiver has a matched filter bandwidth corresponding to the transmitted telemetry pulse shape. Additionally, the victim's receiver has a phase-locked-loop with a fixed bandwidth, (i.e., no hard limiters). Circled numbers on Figure 2.1-1 identify four distinct interference cases.

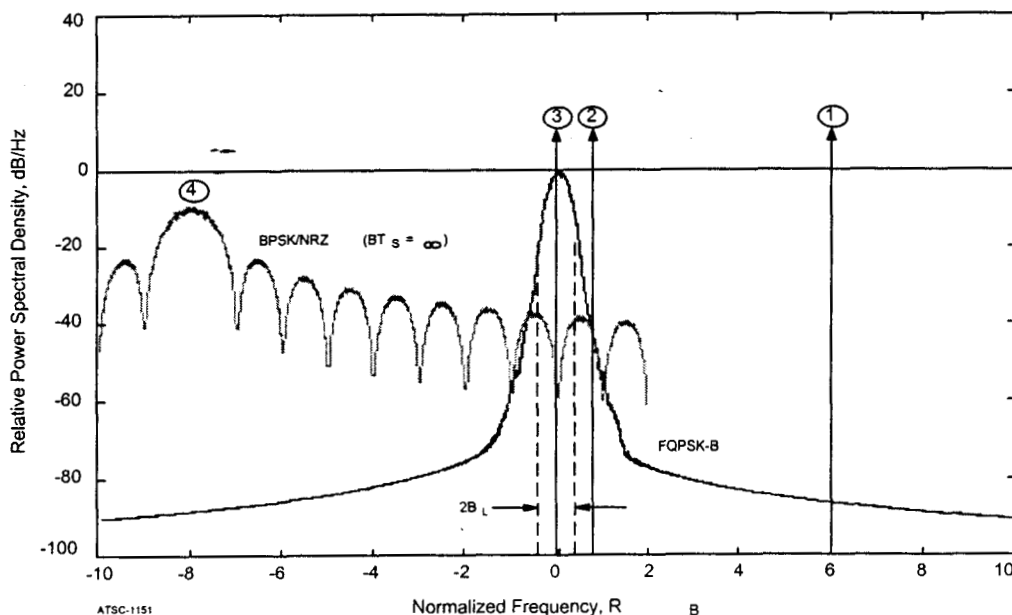


Figure 2.1-1: Interfering Signals

EFFICIENT MODULATION METHODS - INTERFERENCE SUSCEPTIBILITY

2.1.2.1 Case 1: Narrowband Interference Outside Telemetry Bandwidth

Referring to Figure 2.1-1, Case 1 assumes that signals well outside the main spectral lobe will be substantially attenuated by the receiver's filters. For hardware simulations using the receiver depicted in Figure 2.1-3, a narrowband interferer only affects the receiver's operation if it is of sufficient amplitude to cause non-linear operation (e.g., saturation) of a front-end amplifier whose bandwidth is usually wider than the pre-detection filter. Typically, receiver bandwidths progressively narrow as the signal proceeds through the various i.f. amplifiers.

As the interferer's frequency is moved from a frequency far from f_c toward f_c , it eventually falls within the Low Noise Amplifier's (LNA's) bandwidth. If the interferer's level is sufficient, gain compression can result diminishing amplification of the desired signal. Even if the LNA's amplification does not decrease, the interfering signal's amplitude may be increased by the AGC amplifier's gain following the LNA.

Gains and bandpass filter widths are unique to every receiver and it is impractical to consider all combinations. Given a specific receiver design, out-of-band emissions produce substantially the same effect, whatever modulation method is used.

Case 1 need not be considered further because the receiver's behavior is independent of the modulation type used and the purpose of this study is to compare interference susceptibility of efficient modulation schemes. Items common to all modulation types need not be investigated.

2.1.2.2 Case 2: Narrowband Interference In Telemetry Bandwidth Far From f_c

Here, the question is principally how the interference affects the victim receiver's data channel. In this case, the interferer is sufficiently far from the desired signal's center frequency (f_c) so that the receiver filter's roll-off serves as a weighting function attenuating the interfering signal in the same way that noise is reduced. For similar total power levels of desired signal (P_s) and interfering signal (P_I) (i.e., $P_s \approx P_I$), a signal inside the *matched filter's* bandwidth, but comparatively far from f_c , has only a small effect on system's performance.

The amount of the degradation to the desired data signal (S_D) is proportional to power remaining in the interfering signal (P_{TI}), after attenuation by the receiver filter's roll-off characteristic, compared to the total power in the desired signal (P_{TS}) (i.e., $S_D \propto P_{TI} / P_{TS}$).

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2.1.2.3 Case 3: Narrowband Interference In Telemetry Bandwidth and Close to f_c

Initially, it was postulated that all losses described in Case 2 are present together with an additional loss due to additional losses in the receiver's phase-locked-loop. Since the receiver's Costas Loop reconstructs a *carrier* component at f_c , it was believed that the interfering signal would cause phase jitter in the reconstructed carrier.

Costas Loop losses, due to narrowband interference, were evaluated at three locations: at f_c , within the Costas Loop's bandwidth (at $0.0005 \times$ data rate), and outside the Costas Loop's bandwidth but within the *matched filter's* bandwidth (at $0.008 \times$ data rate). Figure 2.1-2 resulted from simulations made using the receiver in Figure 2.1-3. This figure shows Costas Loop phase jitter losses to be substantially independent of the interfering signal's location but very much a function of the interference-to-signal power ratio.

Although initially surprising, this result could have been anticipated considering the mechanization of a Costas Loop. A reconstructed carrier is generated by controlling an oscillator's phase using an error signal derived from orthogonal I-Q channels. Since the transmitted RF spectrum is generated entirely by the data, it is not surprising that an interfering signal lying anywhere within the *matched filter's* bandwidth affects the loop's performance. The amount of performance degradation depends upon the frequency separation between victim and interferer and the matched filter's roll-off characteristics. The same *matched filter* weighting factor argument, affecting interference susceptibility in Case 2 above, applies here.

Case 2 and Case 3 are combined in this study. A high Costas Loop SNR is assured by the relative small Costas Loop-Data bandwidth.

2.1.2.4 Case 4: Wideband Interference In Telemetry Bandwidth and Around f_c

Wideband interference works in the same ways described above but with the distinction that it arises in all three locations simultaneously. The extent to which it degrades the receiver's performance is determined by:

- The characteristics of the interfering signal (i.e., power spectral density)
- The ratio of interfering signal power (P_I) within the receiver filter's bandwidth, considering its roll-off characteristics, to the desired signal's power (P_S) in the same bandwidth.

Susceptibility to wideband interference was determined by centering an unfiltered BPSK interferer, having an equal power to the victim's, far from the victim's center frequency (f_c). The interferer's center frequency is then shifted towards (f_c) so that progressively more of the interferer's signal falls into the victim's bandwidth.

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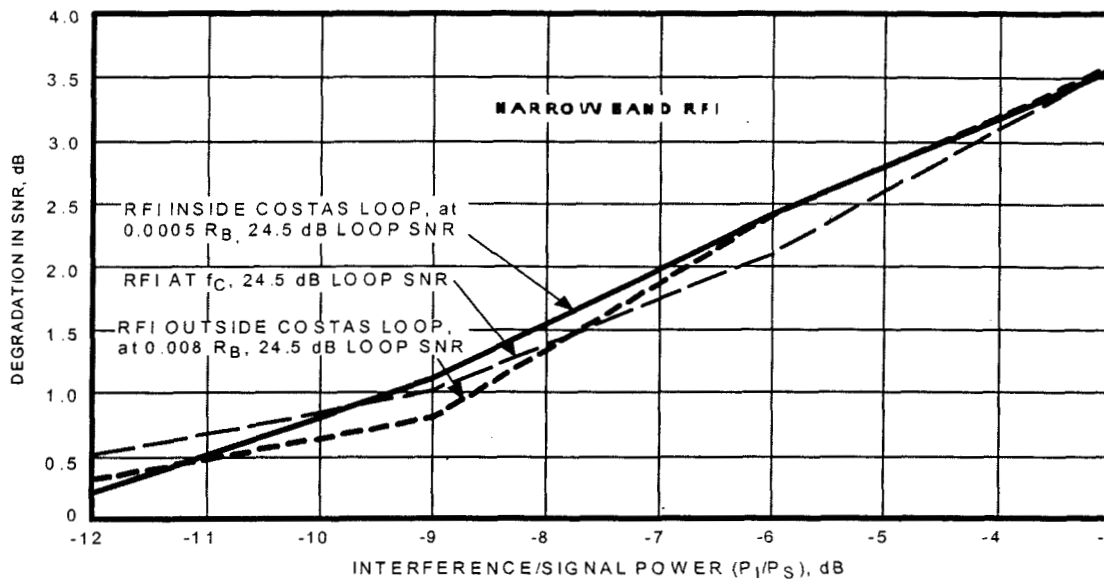


Figure 2.1-2: Costas Loop Narrowband Interference Susceptibility (Hardware)

2.1.3 Receiver Design

The Workplan raises specific questions regarding the receiver's performance in the presence of interference. Degradation due to interference need only be considered in the presence of a receiver. Absent a receiver there will be no interference. How interference affects a receiver depends upon the receiver's design and the position of the interference with respect to the center frequency of the victim signal.

For purposes of this hardware validation, the receiver Phase-Locked-Loop's (PLL's) bandwidth was selected to provide a high Signal-to-Noise-Ratio (SNR) of approximately 25 dB. The telemetry channel employed a Finite Impulse Response (FIR) filter to match the modulated spectrum. For consistency with the Phase 3 study, and for the reasons set forth in Reference 4, all losses were evaluated at a 1×10^{-3} Bit-Error-Rate (BER).

Figure 2.1-3 is a simplified block diagram of the receiver used in the hardware simulations. Named the APRX, it was designed for the EOS AM-1 mission and supports data rates up to 600 Mb/s. Evaluating how interference affects receiver performance requires examining several of its elements. Relevant components will be examined in the sections below discussing different interference types and modulation methods.

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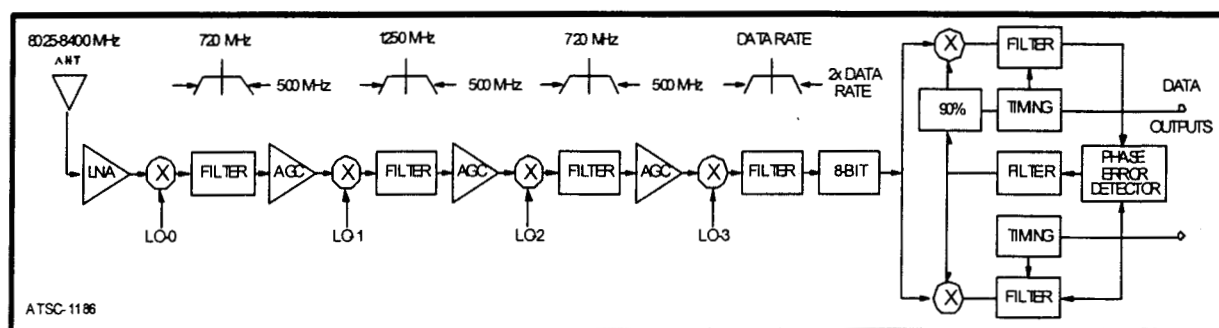


Figure 2.1-3: Simulated EOS AM-1 Receiver (APRX)

In Figure 2.1-3, adjusting the Local Oscillator (LO) frequencies (e.g., LO-0, -1, and -2) shifts the received signal's frequency to first an upper and then a lower filter band edge. Successive filter/amplifier pairs produce a result equivalent to a single pre-detection bandpass filter. Such a design permits fixed bandwidth filters to be used in a receiver which must handle a variety of data rates. A distributed automatic gain control function ensures sufficient signal amplitude while avoiding amplifier saturation. The digital portion of this receiver is a Costas Loop capable of handling both BPSK, QPSK, and OQPSK signals.

Unlike the theoretical analysis, the APRX receiver implements an adjustable post detection filter in the digital signal processor limiting the spectrum to the main lobe. This digital detection (*matched*) filter in the APRX is created by the average time-reversed pulse shape of the received waveform. The pulse shapes of approximately 1,000 random bit-times are time-domain averaged. The waveform is then zero-padded and passed through a discrete-time Fourier transform. Frequency domain detection coefficients are programmed into the APRX. These filters remain unchanged for all simulations, irrespective of the modulation type being evaluated.

2.1.4 Theoretical Calculations vs Hardware Simulations

All interference susceptibility calculations are made using a theoretical model. Computations are based on a baseband filter, a lossless I-Q modulator (see Section 2.1.1), ESA's Solid State Power Amplifier (SSPA) operating in full saturation (Reference 4), a lossless receiver having a "matched" filter, and perfect synchronization of both the carrier and symbol tracking loops. Computed interference susceptibility plots have the word (*Theory*) in their title.

Hardware simulations modeled the same transmitting subsystem described above but substituted a simulation model of the receiver (APRX) shown in Figure 2.1-3 for the perfect device used in the theoretical calculations. Synchronization losses are included. Hardware simulations are included, where possible to: 1) validate the theoretical calculations and 2) provide a more realistic measure of system performance with real hardware. All interference susceptibility plots in Section 3 are based on either theoretical calculations, the hardware simulations, or preferably both methods. Plots based on simulations with perfect synchronization are labeled *Theory* while those employing the APRX are marked *Hardware*.

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2.1.5 Matched Filter

A properly designed *matched filter* optimizes the received signal-to-noise ratio by replicating the pulse shape of the transmitted signal. It attenuates (weights) an interfering signal in the same way that it reduces noise. Absent significant spectral spreading by the SSPA, all of the energy contained in the received spectrum will be recovered while admitting only the minimum amount of noise.

In Phase 4, the focus is on a receiver's interference susceptibility. Consider a congested frequency band, such as 2 GHz, where the likelihood of encountering interference is comparatively high. One can trade power-transfer-efficiency for interference immunity. This best illustrated with an example.

The *Occupied Bandwidth* (99% power containment) of an unfiltered BPSK/NRZ signal is approximately $\pm 10 R_B$. However, 95% of the same signal is contained in only $\pm 1 R_B$. A receiver filter with a $\pm 10 R_B$ bandwidth will recover virtually all of the received energy in the *occupied bandwidth* but it will also have some interference susceptibility over a span of at least $\pm 10 R_B$.

If the receiver filter's bandwidth is reduced from $\pm 10 R_B$ to $\pm 1 R_B$, then approximately 0.45 dB of the received energy will be lost but the receiver's interference immunity will be increased so that an interfering signal lying between ± 1 and $\pm 10 R_B$ will be significantly attenuated. For equivalent roll-off characteristics, the interference immunity is increased several fold. System losses will result from the discarded received signal energy and an increase in Inter-Symbol Interference (ISI).

Absent low noise and/or i.f. amplifier saturation or gain compression resulting from an interfering signal, a receiver's performance in the presence of an interfering signal is determined entirely by its filters.

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3.0 STUDY RESULTS

This section summarizes the results found during the *CCSDS-SFCG Efficient Modulation Methods Study at JPL, Phase 4: Interference Susceptibility*. In evaluating filtered OQPSK, the Workplan specifies a 6-pole Butterworth ($BT = 1.0$) and a Square Root Raised Cosine (SRRC, $\alpha = 0.5$) bandpass filters. JPL's *Efficient Modulation Methods Study: Phase 3* (Reference 4), addressed only baseband filtering, and utilized 3RD order Butterworth ($BT = 2$) and SRRC ($\alpha = 1.0$) low-pass filters. A Butterworth ($BT=2$) filter was selected because losses with a $BT = 1$ filter were nearly 3 dB, when using the constant amplitude *Universal Phase Modulator*, well above the 1 dB SFCG guideline. OQPSK losses were even higher and both were deemed unacceptable. Phase 4 employs an I-Q modulator (see Section 2.1.1 above and Section 3.2.1 below). End-to-end losses with the requested filters are evaluated in Section 3.2.1.

Phase 4 investigated the following modulation types:

1. Unfiltered BPSK (Reference Case)
2. OQPSK using a 3RD order Butterworth low-pass filter ($BT_s = 1$)
3. OQPSK using an SSRC low-pass filter ($\alpha = 0.5$)
4. GMSK ($BT_s = 1.0$)
5. GMSK ($BT_s = 0.5$)
6. FQPSK-B
7. Direct Sequence Spread Spectrum / BPSK

The latter modulation type was included because some SFCG representatives speculated that spread spectrum communications are largely immune to interference and may be even more bandwidth efficient than those studied during Phase 3. Their inclusion in this study was an effort to place spread spectrum modulation in their proper perspective with respect to the other types.

3.1 Unfiltered BPSK (Reference Case)

Figure 3.1-1 is the spectrum of an unfiltered BPSK-NRZ signal. It is identical to the one found in Figure 3.4-2 in Reference 4. This spectrum is representative of an unfiltered BPSK signal after amplification by an SSPA operating in full saturation. Clearly, unfiltered BPSK cannot meet the requirements of either spectrum mask shown in Figure 1.0-1.

Figure 3.1-2a shows the degradation to an unfiltered BPSK signal from the first three cases of narrowband interference. Figure 3.1-2b depicts losses from Case 4, wideband interference, described in Section 2.1.2.4 (see Figure 2.2-1). These plots are based on a matched filter receiver. Data channel losses are plotted as a function of the interfering signal's distance (in R_b) from the victim signal's center frequency, f_c . Different power ratios for Interferer-to-Victim Signal (P_i/P_s) are shown. Note the similarity in the BPSK-NRZ modulation frequency spectrum in Figure 3.1-1 and the data loss in Figure 3.1-2a. For a properly matched filter, the narrowband interference susceptibility relationship is similar to the transmitted spectrum plot.

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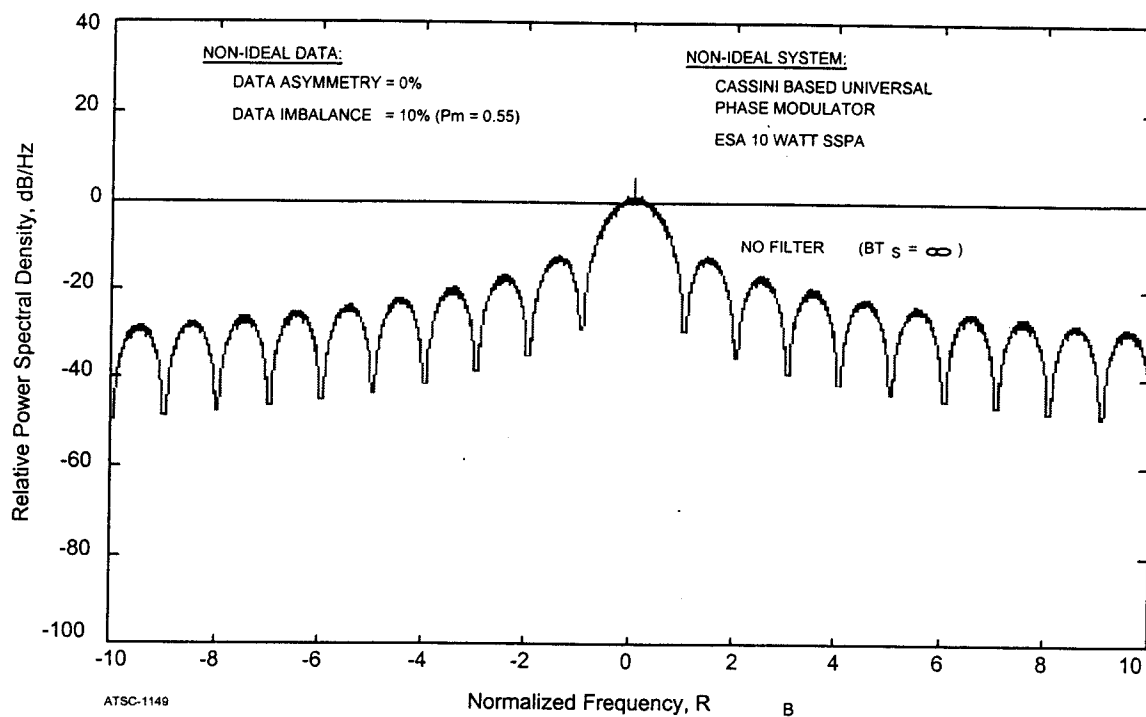


Figure 3.1-1: Unfiltered BPSK Spectrum

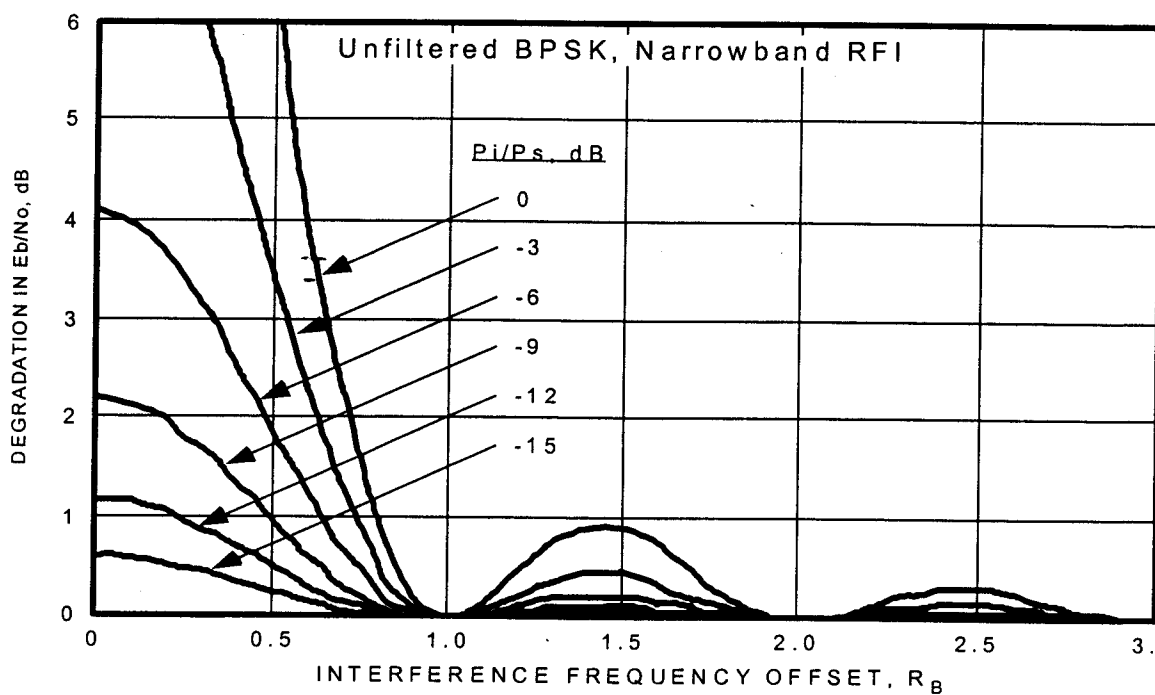


Figure 3.1-2a: Unfiltered BPSK Susceptibility to Narrowband Interference (Theory)

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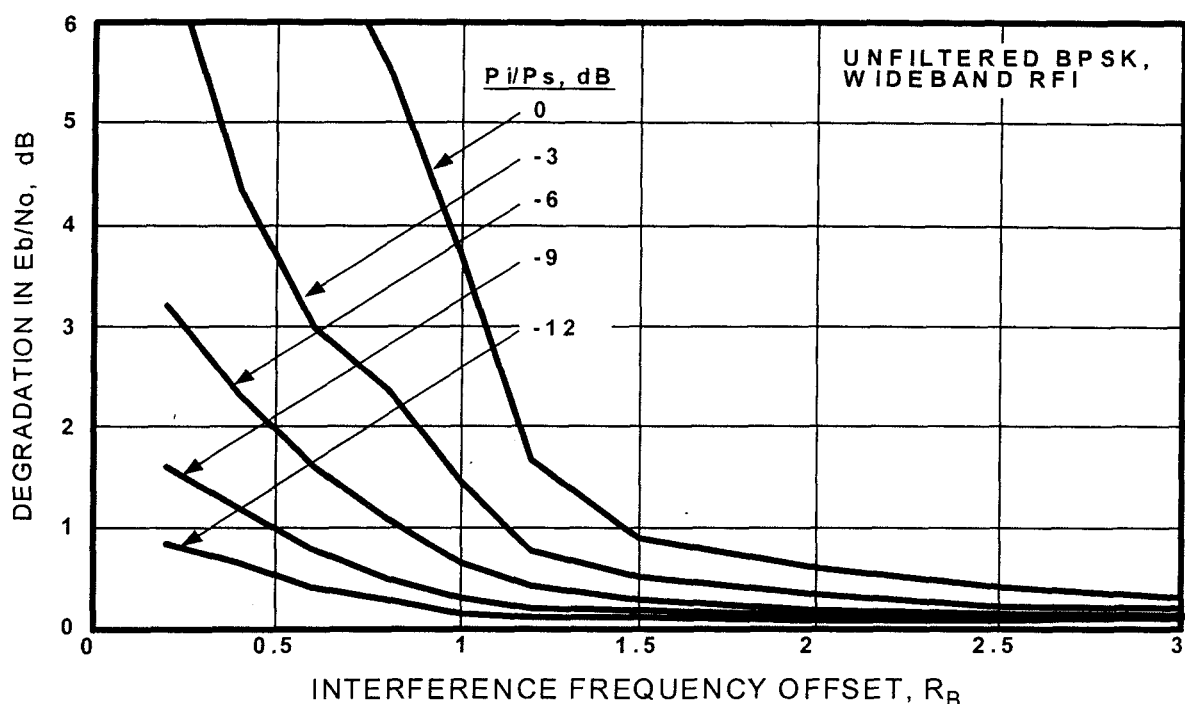


Figure 3.1-2b: Unfiltered BPSK Susceptibility to Wideband Interference (Theory)

First Finding:

To a first order, the receiver's matched filter's characteristics completely determine a modulation method's interference sensitivity function, whether that interference is in-band or out-of-band.

A *matched filter* characteristics should correspond to the transmitted pulse shape. Consider a victim spacecraft using BPSK modulation at a 2 Msps data rate operating in the 2200-2290 MHz band. Assume further that the victim's antenna is aligned with an interferer transmitting an unmodulated carrier with a power equal to the victim's on a channel 5 MHz away. Figure 3.1-2a shows that the victim's receiver experiences a loss of approximately 0.5 dB.

If the *matched filter*'s bandwidth is restricted to $\pm 1 R_B$, only about 90% of the received signal power is admitted resulting in a loss of approximately 0.45 dB. But, reducing the bandwidth also substantially eliminates the receiver's interference susceptibility beyond $\pm 1 R_B$. Whether this is a useful tradeoff depends upon the interference environment (density, relative signal strength, etc.).

Second Finding:

To minimize interference susceptibility, a matched filter's bandwidth should be as narrow as possible after accounting for the minimum acceptable power transfer, and the maximum acceptable ISI.

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Unfiltered BPSK's susceptibility to wideband interference is both different from, yet similar to, that for narrowband interference. Wideband interference susceptibility curves differ from those for narrowband interference which has a shape similar to the RF spectrum. That is expected, since the interfering signal is spread over a wide range of frequencies. The similarity lies in the losses outside the main spectral lobe. For a wideband interferer and victim having equal power, separated in center frequency by $\pm 2.5 R_B$, the victim experiences losses of about 0.5 dB, the same as for the narrowband case. Likewise, for separations of $\pm 1.5 R_B$, there is approximately 1 dB loss in both cases.

Figures 3.1-2a and 3.1-2b are based upon theoretical calculations for unfiltered BPSK estimating the losses resulting from both narrowband and wideband interference. For readers skeptical of such methods, actual data was obtained from an operating system in JPL's Telecommunications Development Laboratory (TDL). The configuration consisted of a Pseudo-Noise (PN) sequence, modulated as an unfiltered BPSK signal in a test transponder, transmitted and being captured by a DSN Block V receiver (the receiver found at DSN stations). A second, narrowband unfiltered BPSK signal (interferer), having the same power as the victim, was injected into the Block V receiver at various frequency offsets. The Bit-Error-Rate (BER) performance for the victim is shown in Figure 3.1-3. Good agreement (0.25 dB) was found when comparing the results from the two methods.

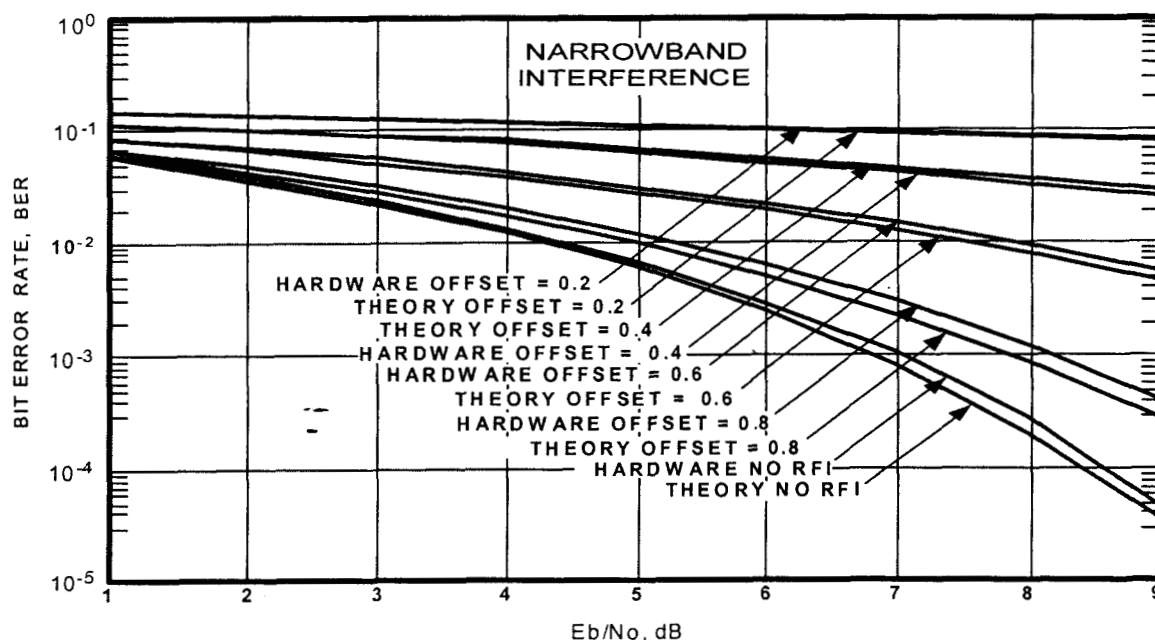


Figure 3.1-3: Theoretical vs Actual Losses to an Unfiltered BPSK Victim

Using the $0.8 R_B$ interferer offset curve in Figure 3.1-3, a BER of 1×10^{-3} (baseline BER for Phase 3) requires an E_b/N_0 of about 8 dB. Comparing with the *No RFI* curve shows that there is approximately a 1 dB loss due to a narrowband interferer, having equal power, $0.8 R_B$ away. Essentially the same value appears in Figure 3.1-2a for the loss at $0.8 R_B$, demonstrating that the theoretical calculations match actual hardware measurements.

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3.2 Filtered OQPSK

Figure 3.2-1 contains frequency spectra for Offset QPSK (OQPSK) modulation using a baseband Square Root Raised Cosine (SRRC) filter ($\alpha = 0.5$), an I-Q modulator (see Section 2.1.1), and ESA's SSPA operating in full saturation. The large Amplitude Modulation (AM) component found in I-Q modulators with baseband filtering eliminates spectral spikes. Bumps in the spectrum result from a 64-tap Finite Impulse Response (FIR) filter in the transmitter. But, even when these variations are averaged, the widened RF spectrum does not quite meet the high data rate SFCG mask at -60 dB. Note the reduced sidelobes in Figure 3.2-1 as compared to the reference case (Figure 3.1-1).

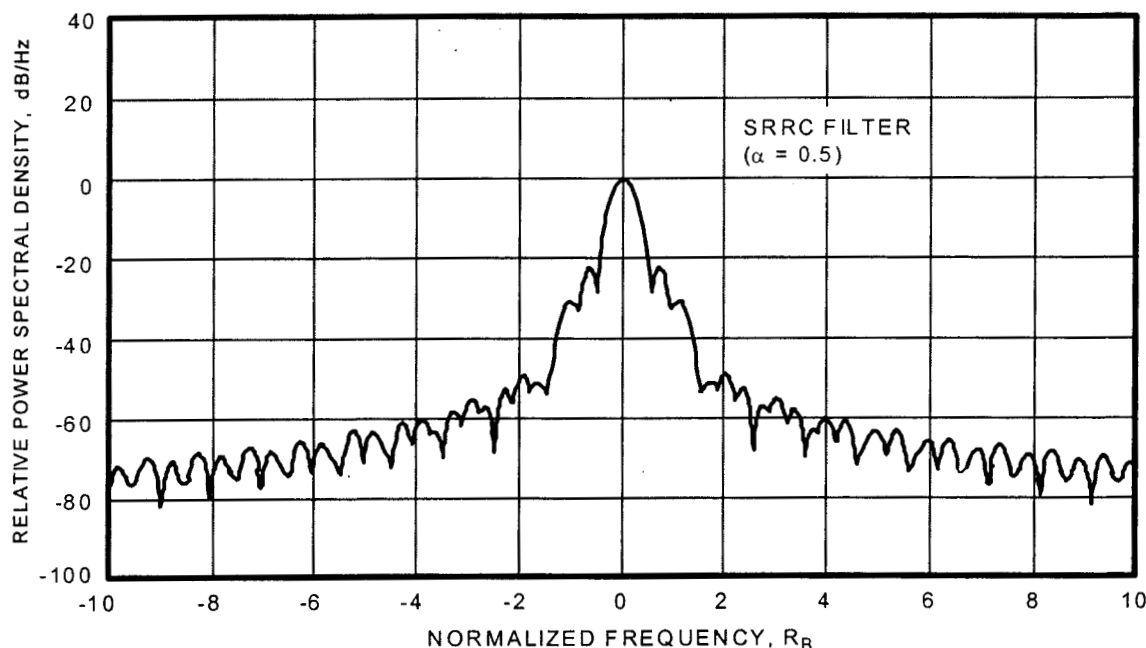


Figure 3.2-1: OQPSK Modulation Spectra with an SRRC Filter ($\alpha = 0.5$)

Section 2.1.1.1 described the proper method for generating an SRRC waveform. The RF spectrum shown in Figure 3.2-1 is the product of a correctly generated SRRC waveform and the I-Q modulator described in Section 2.1.1. Spectral spreading, due to the AM component in the I-Q modulator, is clearly evident in Figure 3.2-1.

OQPSK's susceptibility to narrowband interference with Butterworth ($BT_s = 1$) and SRRC ($\alpha = 0.5$) baseband filters is shown in Figures 3.2-2a, 3.2-2b, and 3.2-3. Compared to the susceptibility of the unfiltered BPSK-NRZ reference, it is clear that the interfering signal must be much closer to the desired signal's center frequency, f_c , before significant degradation occurs. With a narrowband interferer of equal power to the victim, unfiltered BPSK suffers degradations of 0.5 and 1 dB at $f_c \pm 2.5 R_B$ and $\pm 1.5 R_B$ respectively, whereas OQPSK, with a Butterworth filter ($BT_s = 1$), only reaches these same levels at $f_c \pm 0.5 R_B$ and $\pm 0.45 R_B$.

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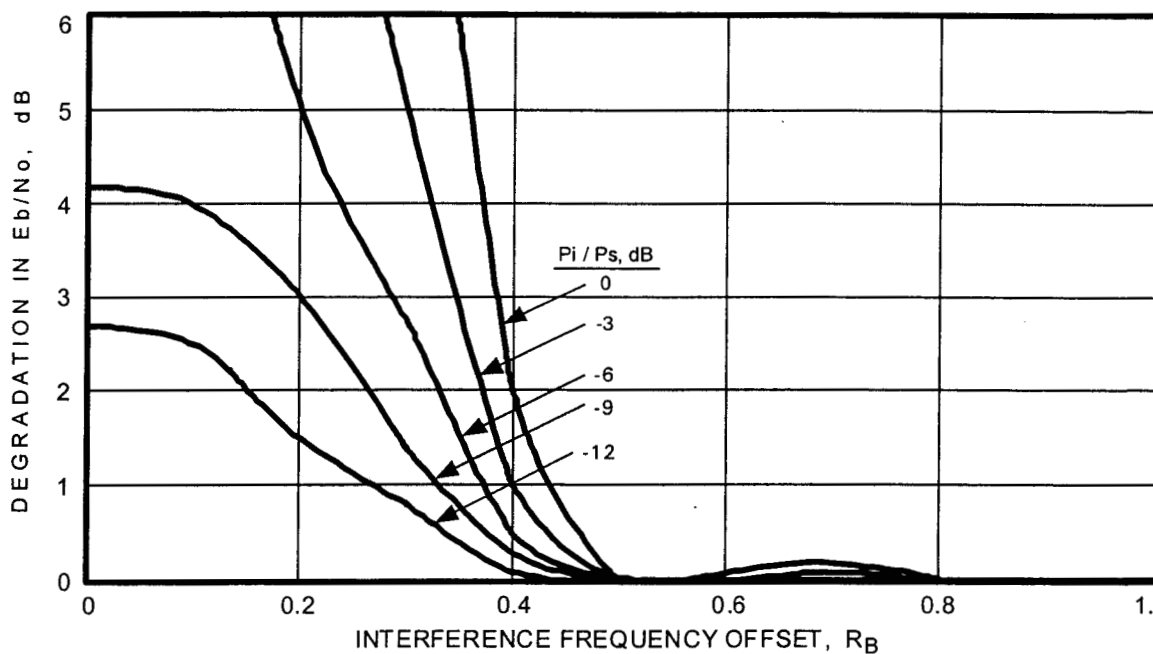


Figure 3.2-2a:
OQPSK (Butterworth, $BT_s = 1$) Susceptibility to Narrowband Interference (Theory)

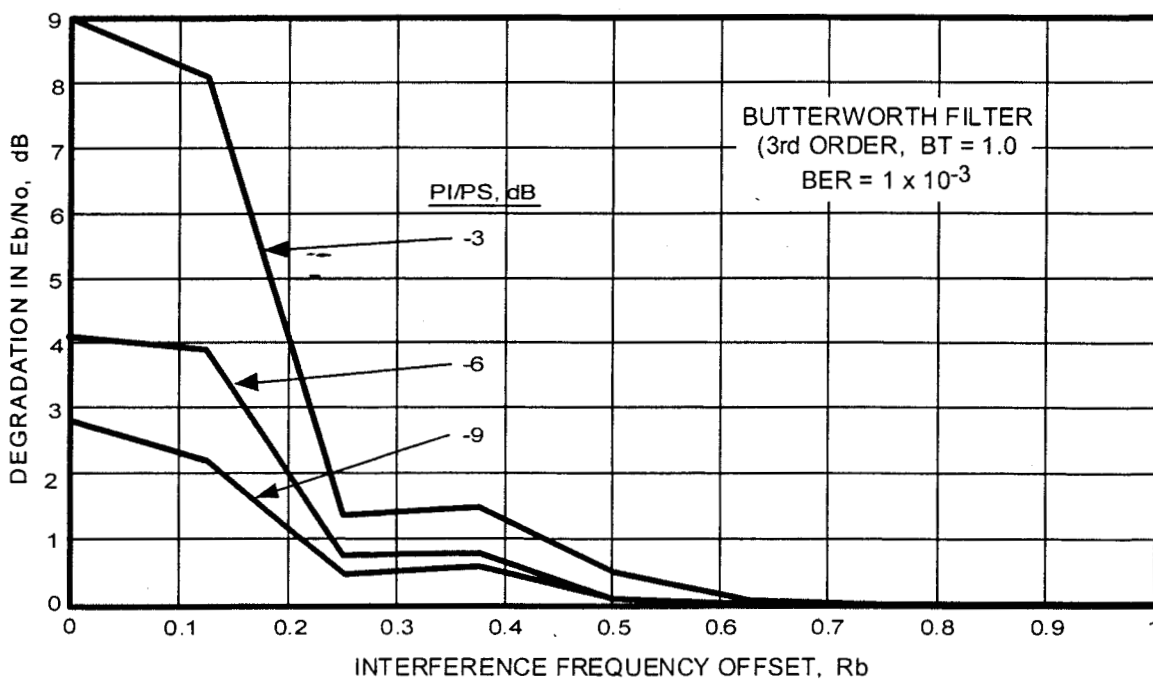


Figure 3.2-2b:
OQPSK (Butterworth, $BT_s = 1$) Susceptibility to Narrowband Interference (Hardware)

EFFICIENT MODULATION METHODS - INTERFERENCE SUSCEPTIBILITY

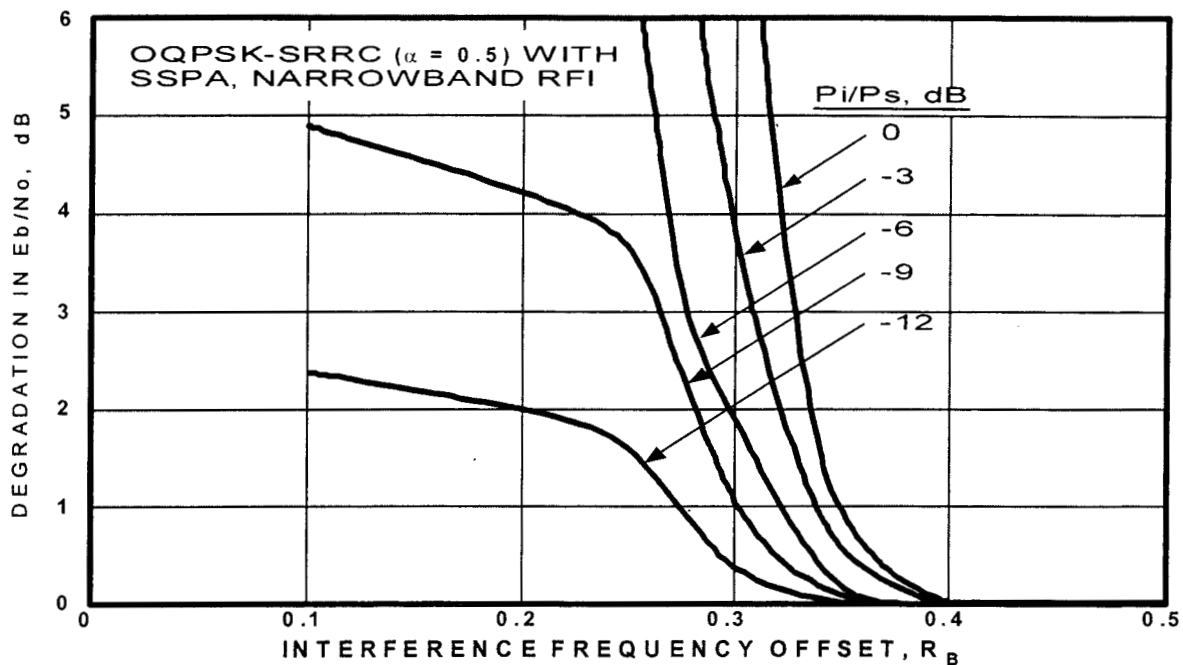


Figure 3.2-3:

OQPSK (SRRC, $\alpha = 0.5$) Susceptibility to Narrowband Interference (Theory)

Substituting a baseband SRRC filter ($\alpha = 0.5$) for the Butterworth reduces interference susceptibility even further. Now, losses of 0.5 and 1 dB occur at approximately $f_c \pm 0.37 R_B$ and $\pm 0.35 R_B$ respectively. These results follow from the facts that:

1. OQPSK's spectrum is more compact than BPSK so the *necessary bandwidth* is reduced.
2. Baseband filtering rapidly attenuates spectral sidelobes with the result that they are outside the *necessary bandwidth* and significant interference will not occur.

Third Finding:

When comparing interference susceptibility of different modulation methods, those with more compact spectra have more interference immunity than modulation types requiring larger bandwidths, provided that the receiver has a properly matched filter and the spectral width remains narrower at all levels.

This finding is contrary to the popular belief that the more compact a modulation spectra, the more susceptible it will be to interference. This erroneous idea can probably be traced to the notion that spread spectrum modulation has a high degree of interference immunity because its signal is spread over such a large frequency band that a narrowband interferer has an insignificant effect.

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That generalization is incorrect because the processes of spread spectrum and bandwidth efficient modulation are entirely different. In spread spectrum modulation, a PN code, having a chip rate much greater than the data rate (100 to 1,000 times), is mixed with the data to spread the transmitted spectra over a broad range of frequencies (100 to 1,000 times the original bandwidth). At the receiver, a local model of the PN code is cross-correlated with the received signal to de-convolve the spectrum into that of the original data. This cross-correlation process causes the narrowband interference to be spread over a broad range of frequencies with the result that it no longer has significant power within the data bandwidth.

Conversely, bandwidth efficient modulation simply uses the power that would have been spread over a larger range of frequencies and concentrates that same transmitted power in a smaller bandwidth. When this occurs two things happen:

Corollary 1 to Third Finding:

The power spectral density of a bandwidth efficient modulated signal is increased with respect to a non-baseband filtered modulation, reducing its susceptibility to a narrowband interferer having the same total transmitting power.

and

Corollary 2 to Third Finding:

If the receiver has a properly matched filter, there will be virtually no susceptibility to interference lying outside its bandwidth. Therefore, a narrowband interferer, occurring within the victim's allocated frequency band, has a lower probability of falling within the victim's narrower bandwidth.

Figure 3.2-4 depicts the susceptibility of OQPSK modulation with an SRRC ($\alpha = 0.5$) filter to wideband interference based on a theoretical analysis. Like those for the narrowband interference, degradation in E_B/N_0 is plotted as a function of interferer-victim separation. Seven points were computed and fitted with the curve shown in Figure 3.2-4. As with the other curves in this report, losses were measured at a BER of 1×10^{-3} corresponding to an E_B/N_0 of 8 dB.

Comparing Figures 3.2-3 with 3.2-4 it is clear that a SRRC filtered OQPSK receiver is more susceptible to a wideband interferer of equal power than to narrowband interference at the same power. A wideband interferer produces a 1 dB degradation at $0.9 R_B$, whereas that same loss occurs at $0.35 R_B$ when the interference is from a narrowband source. Why that is so becomes clear when one inspects Figure 3.1-1 showing the spectrum for an unfiltered BPSK signal. The interferer's main spectral lobe overlaps the victim's main spectral lobe so that there will be energy at the victim's f_c . Limiting the degradation to 0.5 dB requires the interferer's center frequency to be at least $1 R_B$ from the victims's.

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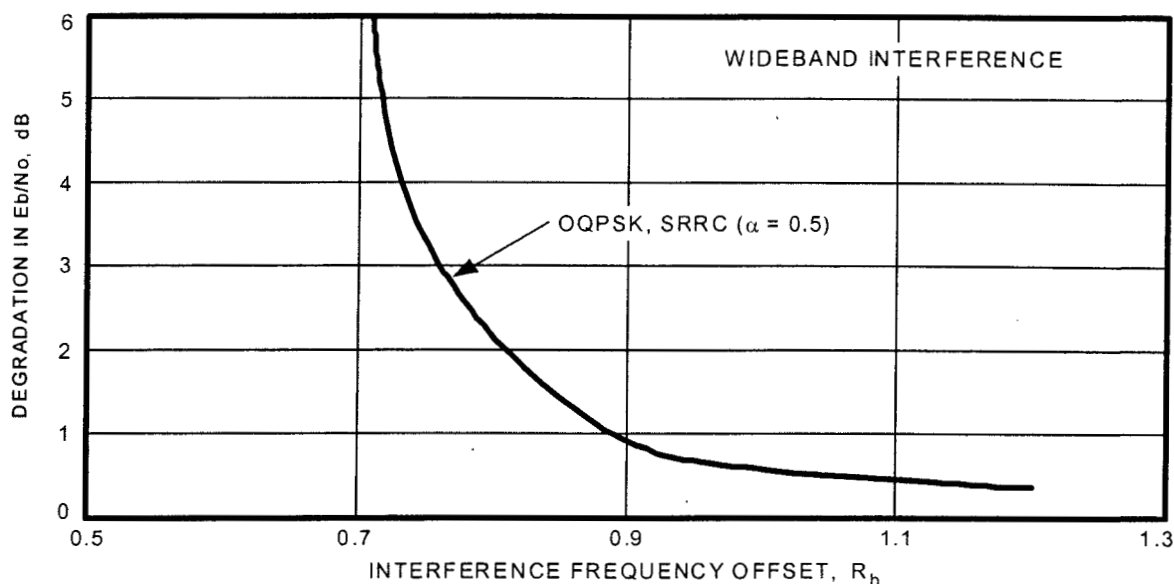


Figure 3.2-4: OQPSK (SRRC, $\alpha = 0.5$) Susceptibility to Wideband Interference (Theory)

3.2.1 OQPSK Bit-Error-Rate With An I-Q Modulator

Phase 3 studies demonstrated that the *Universal Phase Modulator* was unsuitable for OQPSK. Phase 4 utilized an I-Q modulator. There was suspicion that this change may have rendered the OQPSK BER measurements in Phase 3 invalid. Therefore, a study was undertaken to reevaluate losses with the specified configuration.

Since the bandwidths of both filters were changed from the values used in Phase 3, new BER curves were generated for a system containing an I-Q modulator and both baseband 3-pole Butterworth ($BT = 1$) and SRRC ($\alpha = 0.5$) filters. As before, losses were evaluated at a $BER = 1 \times 10^{-3}$ ensuring virtually error-free channel performance with the CCSDS concatenated code.

Figures 3.2-5a and 3.2-5b depict BER as a function of the received E_b/N_0 for Butterworth ($BT_s = 1$) and SRRC ($\alpha = 0.5$) filters respectively when used in a transmitting system containing an ideal I-Q modulator. An ideal modulator has perfect amplitude and phase balance between the I and Q channels. CCSDS Recommendations 401 (4.2-14a) B-1 and 401 (2.4.14b) B-1 specify a maximum amplitude imbalance of 0.2 dB and a maximum phase imbalance of 2 degrees for an OQPSK modulator. If these *worst case* conditions occur, the degradation in E_b/N_0 will be about 0.8 dB at a $BER = 1 \times 10^{-3}$.

Both Butterworth and SRRC filters produce losses of about 0.6 dB, considerably lower than those found in the Phase 3 study. However, the Phase 3 study included filtering and synchronization losses which are not considered in the Phase 4 study.

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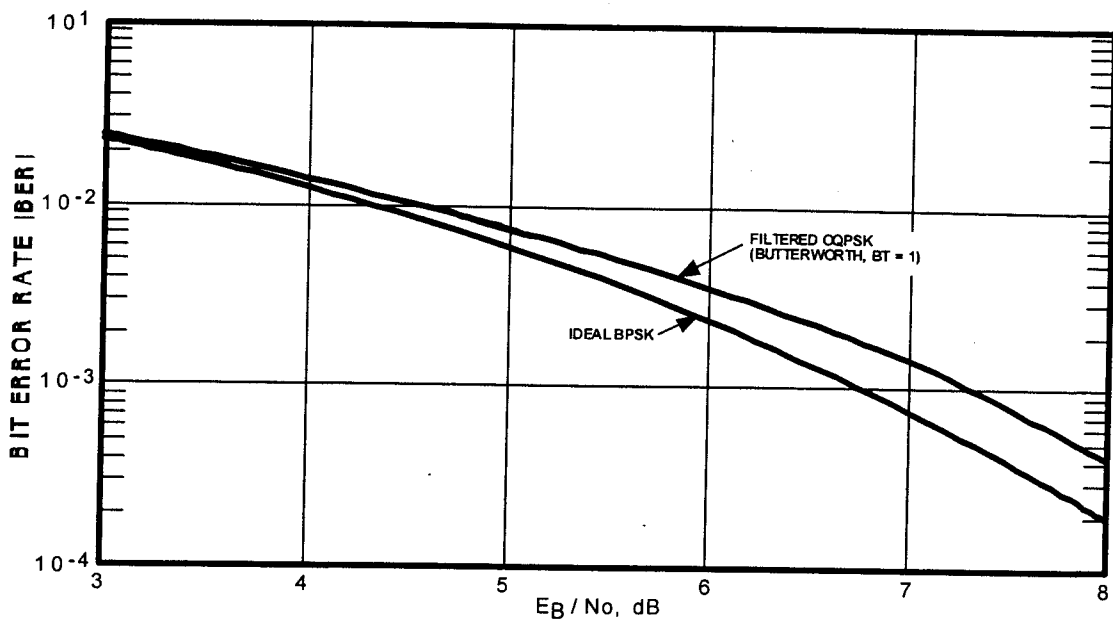


Figure 3.2-5a: OQPSK BER with Butterworth (BT = 1) Baseband Filter

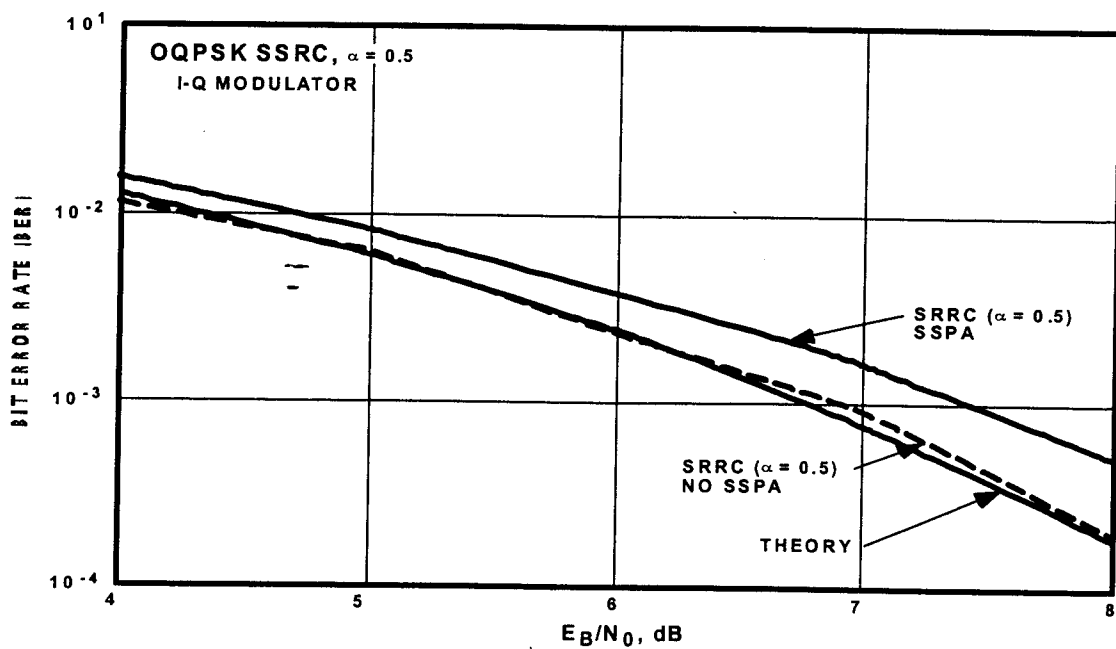


Figure 3.2-5b: OQPSK BER with SRRC ($\alpha = 0.5$) Baseband Filter

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During the Phase 3 study, it was found that end-to-end losses and RF spectrum width are inversely related. The narrowest RF spectrum width was obtained with constant envelope modulation. The Universal Phase Modulator, a linear analog device, has a relatively flat amplitude vs phase shift characteristic producing a very compact RF spectrum. However, the end-to-end losses were found to be ≥ 3 dB for Butterworth ($BT_s = 1$) and SRRC ($\alpha = 1$) filters.

Conversely, I-Q modulators with baseband filtering have significant AM because the phase shift is generated by adding the amplitudes of two signals differing in phase by 90 degrees. With a squarewave input, each leg is either ± 1 at all times. However, narrowband ($BT = 1$ or $\alpha = 0.5$) baseband filtering produces a constantly varying amplitude in both legs of the modulator. When multiplied, the result also varies in amplitude. A signal with a large AM component amplified by a non-linear device (SSPA) produces sideband re-growth and the transmitted spectrum is widened. For this reason I-Q modulators were not used in the Phase 3 study.

Spectral broadening can be observed in Figure 3.2-1 generated using an SRRC ($\alpha = 0.5$) filter. Although close, the resulting spectrum will not quite meet the SFCG mask at the -60 dB level. ESA's study (Reference 5) places a simple Butterworth ($BT = 1.2$) filter at both an intermediate frequency (i.f.) and after power amplification. Their study showed that this configuration will meet the SFCG mask requirements.

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3.3 GMSK

Gaussian Minimum Shift Keying (GMSK) is widely used in Personal Communications Systems (PCS). However, the characteristics of a PCS system differ from those needed in a *space sciences* application. Generally, PCS are characterized by strong signals which can tolerate relatively large end-to-end losses. The inverse is true for most space missions.

During the Phase 3 *Efficient Modulation Methods Study*, GMSK was found to be one of two modulation types that was significantly more bandwidth efficient than the others. Systems using GMSK were determined to have no difficulty in complying with the SFCG mask.

The *Workplan* for the interference susceptibility study requested two GMSK filters be evaluated: $BT_s = 1$ and $BT_s = 0.5$. As before, both narrowband and wideband interference susceptibility was evaluated. Figures 3.3-1a and 3.3-1b show the susceptibility of a GMSK system to narrowband interference. These Figures are for filter bandwidths of $BT_s = 1$ and $BT_s = 0.5$ respectively.

Surprisingly, GMSK ($BT_s = 0.5$) is slightly more susceptible to narrowband interference than is OQPSK using an SSRC ($\alpha = 0.5$) filter. That is evident when comparing Figures 3.3-1b and 3.2-3 where interference degrades GMSK's E_B/N_0 by 0.5 dB at $f_c \pm 0.5 R_B$ rather than at $f_c \pm 0.37 R_B$ for the SSRC filtered OQPSK.

Such an unexpected result precipitated an investigation to explain this result. Figure 3.3-2 is the RF spectrum for a GMSK modulated signal measured in Phase 3 (Reference 4). The 2-sided spectral width of SSRC ($\alpha = 0.5$) OQPSK at 60 dB below the peak is $7.3 R_B$ (Figure 3.2-1) compared to only $2 R_B$ for GMSK (Figure 3.3-2). However, at 20 dB below the peak, the respective 2-sided spectrum widths are $0.8 R_B$ and $1.0 R_B$ showing that SSRC filtered OQPSK's spectrum near its peak is narrower than the one for GMSK! It remains narrower at all levels above 20 dB below the peak. This is the region of greatest susceptibility to interference with the result that a narrowband interferer begins to affect GMSK at $\pm 0.55 R_B$, whereas an SSRC filtered OQPSK receiver only detects the same interferer at $\pm 0.4 R_B$.

This finding seems to suggest that SSRC filtered OQPSK modulation is superior to GMSK. That might be so if narrowband interference susceptibility were the only criterion. It is not. The principal motivation for the Efficient Modulation Methods study is to determine how many more spacecraft can operate in currently allocated frequency bands without causing mutual interference. It was established in Phase 3 that an Earth orbiting spacecraft's telemetry signal, received at a ground station, can undergo a 30 dB variation in signal level between apogee and perigee (see Reference 4, Section 4.1.2).

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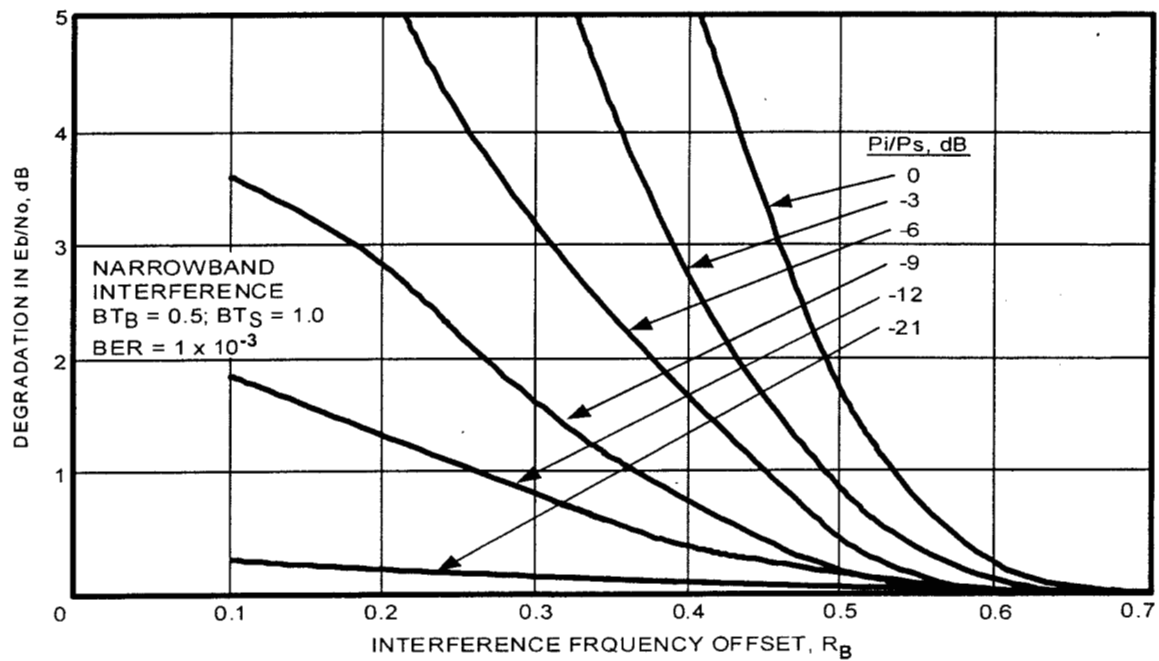


Figure 3.3-1a: GMSK ($BT_s = 1$) Susceptibility to Narrowband Interference (Theory)

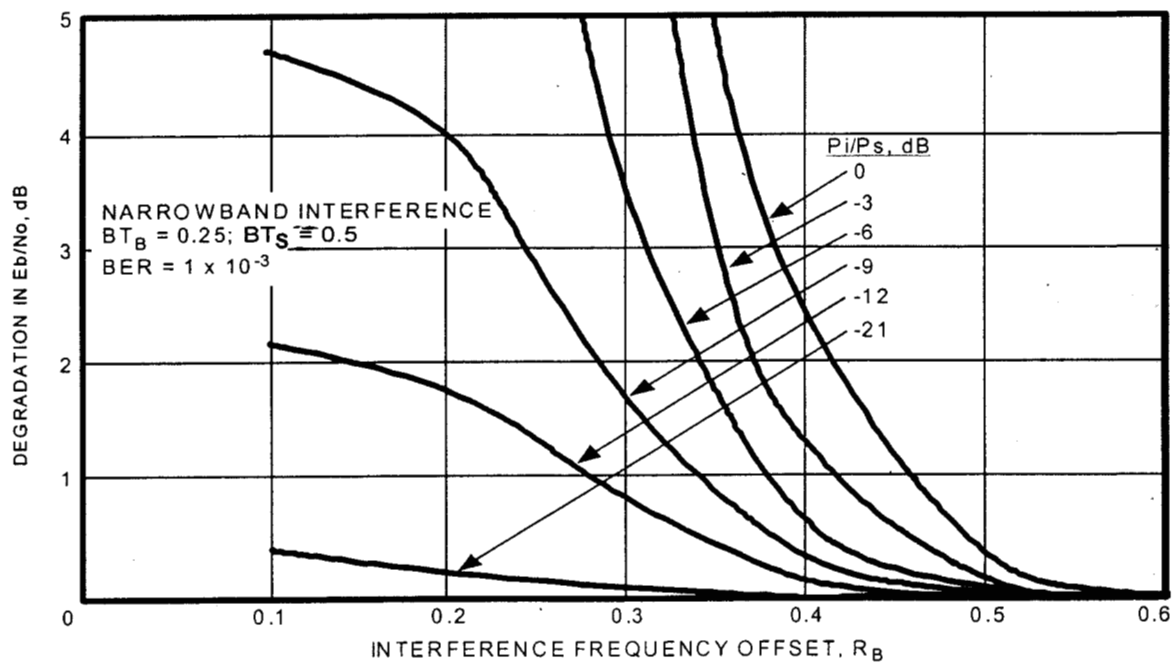


Figure 3.3-1b: GMSK ($BT_s = 0.5$) Susceptibility to Narrowband Interference (Theory)

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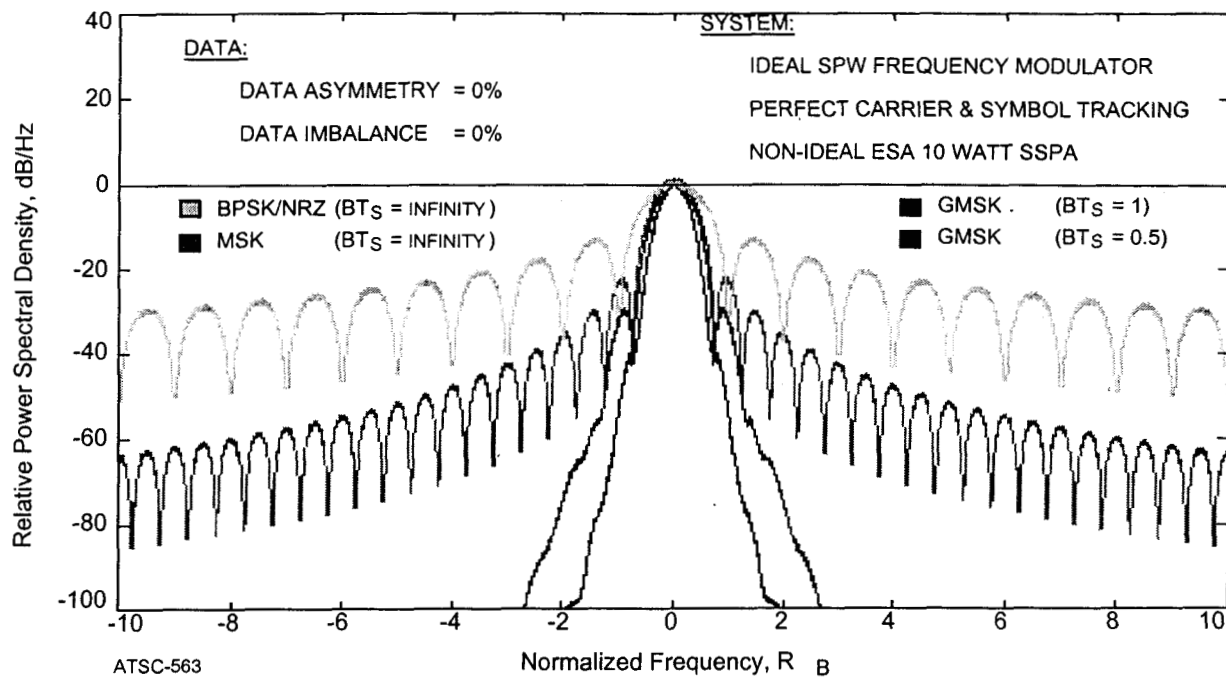


Figure 3.3-2: GMSK ($BT_s = 0.5, 1$) Spectra

For complete, interference free operation, RF spectra of two spacecraft on adjacent frequencies should not be permitted to overlap at levels above 20 dB below their peak. Since one spacecraft's signal can be 30 dB stronger than the other's, the greater of the two must be at least 50 dB below its peak, while the weaker will be 20 dB below its peak before spectral intersection can occur. This criteria sets the minimum adjacent channel spacing. Leaving an additional 10 dB safety factor, means that channel spacing should be determined by the spectral width at 60 dB below the peak.

Now the choice is clear. GMSK has a spectral width of $2 R_B$ at 60 dB below the peak whereas SRRC filtered OQPSK is $7.3 R_B$ at the same level. The inescapable conclusion is that GMSK permits more than $3\frac{1}{2}$ times as many spacecraft to operate in a given bandwidth than does SRRC filtered OQPSK with only a minor increase in interference susceptibility.

Comparing Figure 3.3-3 for GMSK ($BT = 0.5$) with Figure 3.2-4 for SRRC ($\alpha = 0.5$) filtered OQPSK shows that they exhibit about the same degradation to wideband interference. Both have about a 1 dB loss at a $1 R_B$ separation.

In summary, interference immunity is only one term in the equation for selecting the best modulation method. That determination must consider a multiplicity of factors while always keeping focused on the central objective of the Efficient Modulation methods study - packing the maximum number of users in a frequency band having fixed edges while maintaining mutual interference immunity. Highest RF spectrum utilization will be obtained using modulation types with very narrow spectra at 60 dB below their peak (see Table 3.5-1 below).

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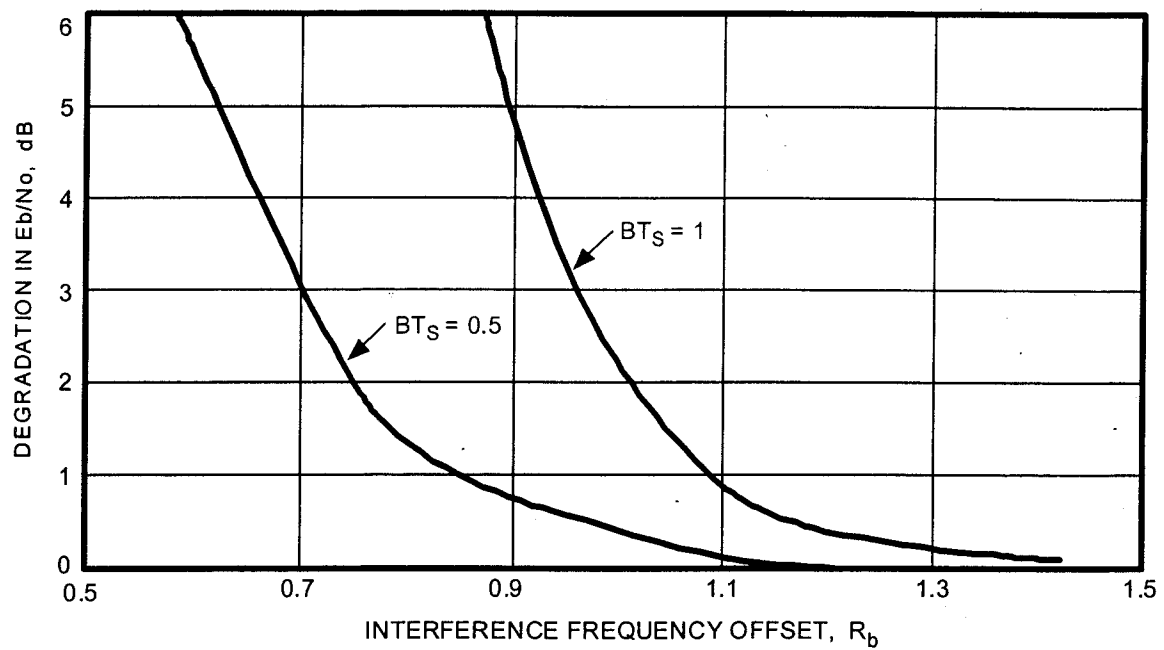


Figure 3.3-3: GMSK Susceptibility to Wideband Interference (Theory)

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3.4 FQPSK-B

In the Phase 3 *Efficient Modulation Methods Study*, Feher Quadrature Phase Shift Keying (FQPSK) modulation, a.k.a. Feher patented OPSK, was found to be the most bandwidth efficient modulation tested. It was better than GMSK ($BT_s = 0.5$). A patent for FQPSK-B and other modulation schemes is held by Dr. Kamilo Feher who assigned certain rights to Digcom Inc., El Macero, California.

Pursuant to a Technology Cooperation Agreement between Digcom and JPL and Non-Disclosure Agreements between Digcom and several persons at JPL, Dr. Feher provided the authors with key proprietary parameters for analyzing the performance of FQPSK-B. A commercially manufactured FQPSK-B modem was also furnished by Digcom permitting the authors to verify their simulation results. FQPSK-B was the only modulation type studied where simulations could be validated using actual hardware.

Figures 3.4-1a and 3.4-1b show FQPSK-B's narrowband interference susceptibility based on theoretical computations and hardware simulations respectively. Like the GMSK ($BT_s = 0.5$), the theoretical performance of FQPSK-B in the presence of narrowband interference (Figure 3.4-1a) shows its susceptibility to narrowband interference starts at $f_c \pm 0.55 R_B$. For an interferer having equal power to the victims, a 0.5 dB degradation is reached at $f_c \pm 0.5 R_B$ and a 1 dB loss occurs at $f_c \pm 0.45 R_B$. FQPSK-B's susceptibility to narrowband interference is about the same as that for GMSK ($BT_s = 0.5$) which experiences a degradation in E_b/N_0 of 0.5 and 1 dB at $\pm 0.49 R_B$ and $\pm 0.47 R_B$ respectively. Neither are quite as good as SRRC ($\alpha = 0.5$) filtered OQPSK where the corresponding points occur at $0.37 R_B$ and $0.35 R_B$. FQPSK-B's slightly greater narrowband interference susceptibility than that for SRRC filtered OQPSK is likely due to a slightly broader spectrum in the vicinity of f_c . Please refer to Section 3.3 for the explanation.

Caution:

These comparisons are based on theoretical calculations and the investigators' best estimates of actual system performance. The differences noted are second order and well within the uncertainties of the analytical techniques employed. Readers should treat OQPSK, GMSK, and FQPSK-B as having approximately equal narrowband interference susceptibility.

Figure 3.4-1b shows FQPSK-B's narrowband interference susceptibility based on hardware simulations. Hardware simulations are made at specific points and the straight lines connecting those are not representative of actual system performance between discrete points. Comparing the theoretical computations with the hardware simulations produces some interesting observations:

1. The effects of narrowband interference begin at $f_c \pm 0.5 R_B$.
2. At a $P_I/P_S = -3$ dB, hardware interference susceptibility is greater than predicted by theory.
3. At a $P_I/P_S = -6$ dB, hardware interference susceptibility is lower than theory.
4. At a $P_I/P_S = -9$ dB and below, hardware interference matched theory.

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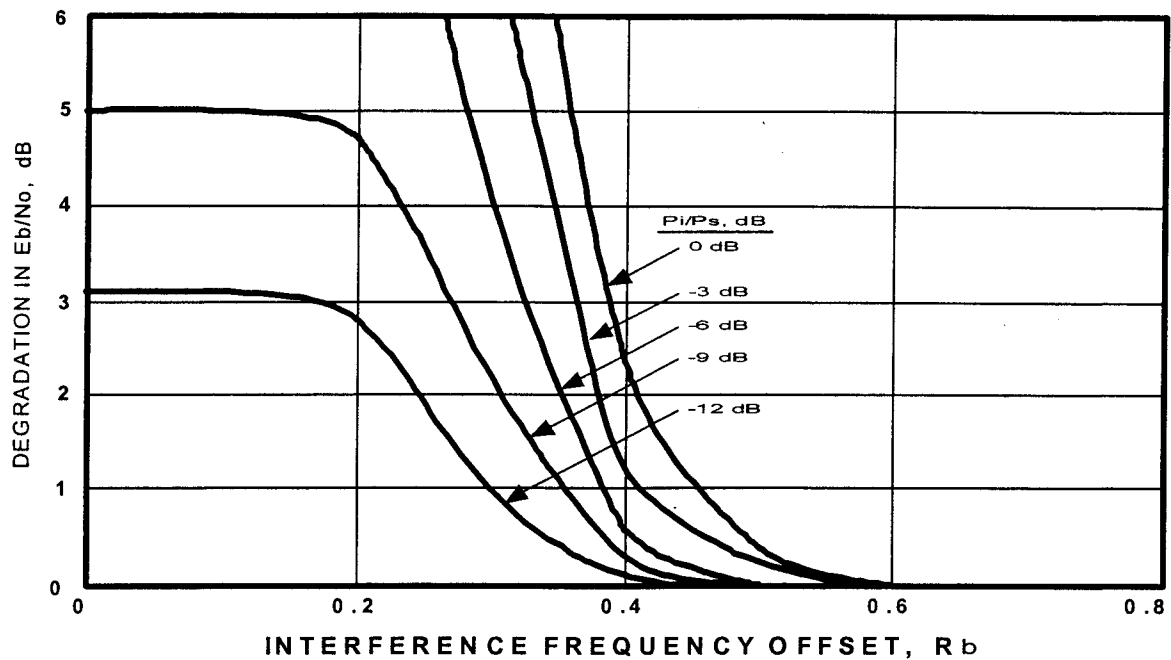


Figure 3.4-1a: FQPSK-B Susceptibility to Narrowband Interference (Theory)

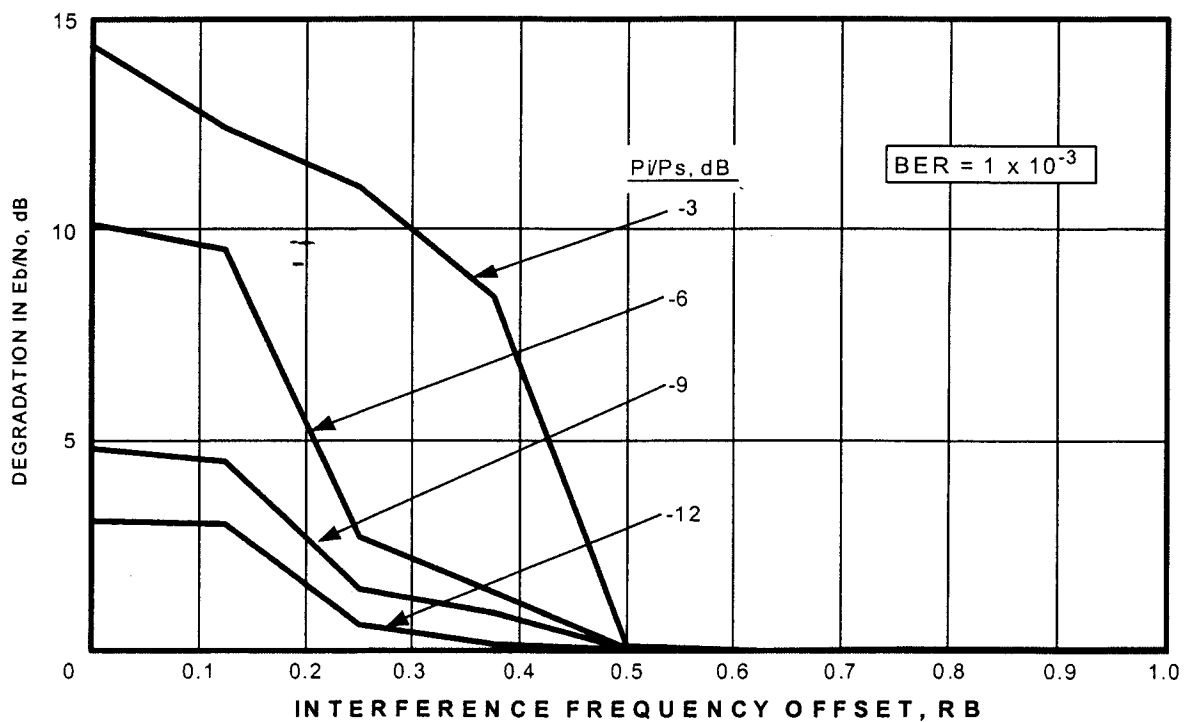


Figure 3.4-1b: FQPSK-B Susceptibility to Narrowband Interference (Hardware)

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These observations require an explanation. First, hardware simulations corroborate that narrowband interference first affects FQPSK-B around $f_c \pm 0.55 R_b$. At greater separations an interferer with equal power will not affect the receiver provided it includes a proper filter.

Second, the poorer performance shown by the hardware simulations, when compared with theoretical calculations at a $P_I/P_S = -3$ dB (and above), is most likely due to synchronization failure. Recall that theoretical computations assume ideal synchronization whereas hardware simulations are based upon the APRX receiver shown in Figure 2.1-1 which does include synchronization losses. At high interference levels, synchronization losses can be expected to increase significantly. Some of this loss may result from the filtering used in the receiver which was optimized for Butterworth filtered OQPSK but not for FQPSK-B.

Third, the more interesting case is the better performance shown by the hardware simulations at a $P_I/P_S = -6$ dB and below as compared with theoretical computations. Again one must examine the filtering in the APRX. This filter matches an *average* of the transmitted spectrum and is narrower than the "matched" filter used in the theoretical simulations. While narrowband interference susceptibility is reduced, the end-to-end losses are increased and were not measured for this study. Essentially, the filter built into the APRX is filtering signal as well as interference.

Figure 3.4-2 compares FQPSK-B's susceptibility to wideband interference with Butterworth filtered OQPSK. They are based on hardware simulations. FQPSK-B is always better than OQPSK, by as much as 3 dB at low values of P_I/P_S . Moreover, FQPSK-B experiences a loss of approximately 10 dB for a $P_I/P_S = -5$ dB which corresponds to the value found in the narrowband interference case.

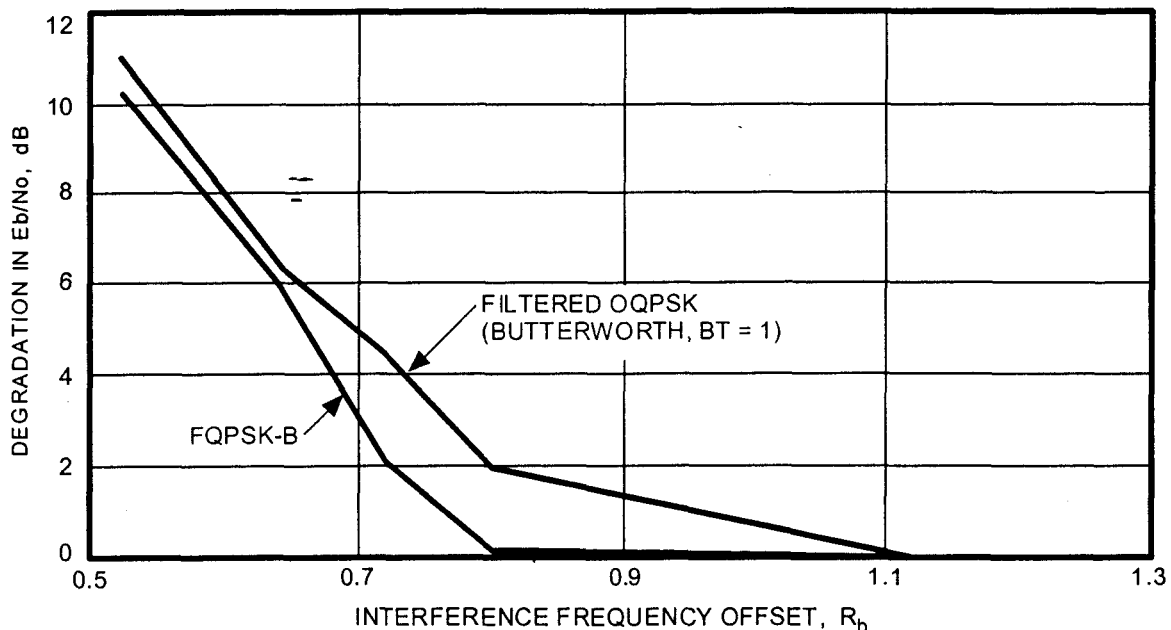


Figure 3.4-2: FQPSK-B Susceptibility to Wideband Interference (Hardware)

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3.4.1 Special FQPSK-B Study

A special JPL study was undertaken in support of the Advance Range Telemetry (ARTM) Project at Edwards Air Force Base (EAFB). Personnel designing this new missile range telemetry system were interested in FQPSK-B because it permits more users to operate in the allocated band than is possible with their present modulation method. One of their principal concerns was Adjacent Channel Interference (ACI). Although the report describing the study results is not public because it contains proprietary Digcom information, it is possible to provide some of the findings from that independent study.

ARTM's goals are similar to those of the *CCSDS-SFCG Efficient Modulation Methods Study*: *how can more independent users be packed into a given bandwidth without sacrificing interference immunity?* ARTM personnel believed that Adjacent Channel Interference (ACI) is the key parameter for determining a modulation type's susceptibility to interference from another signal. This study also addressed that question. ACI implies another user, transmitting data on an adjacent RF frequency. If the frequency separation is insufficient there will be interference degrading the victim's data.

There is a key difference between this study and the one for ARTM. This Phase 4 study uses unfiltered BPSK as the wideband interferer while the one for ARTM used a like signal. Thus, the ARTM study used adjacent FQPSK-B signals to determine the minimum separation between two users transmitting the same data rate.

Figure 3.4-3 shows the ACI (in dB) as a function of signal separation for two receiver filters having different roll-off characteristics. Since actual FQPSK-B filter parameters are Digcom proprietary, the complete set of characteristics cannot be listed. It is sufficient to note that the sharper the roll-off, the lower the ACI. For two FQPSK-B signals of equal power spaced $1 R_B$ apart, a receiver having the filter with the more gradual roll-off only permits 1/10,000th of the adjacent channel's power to enter the victim's receiver.

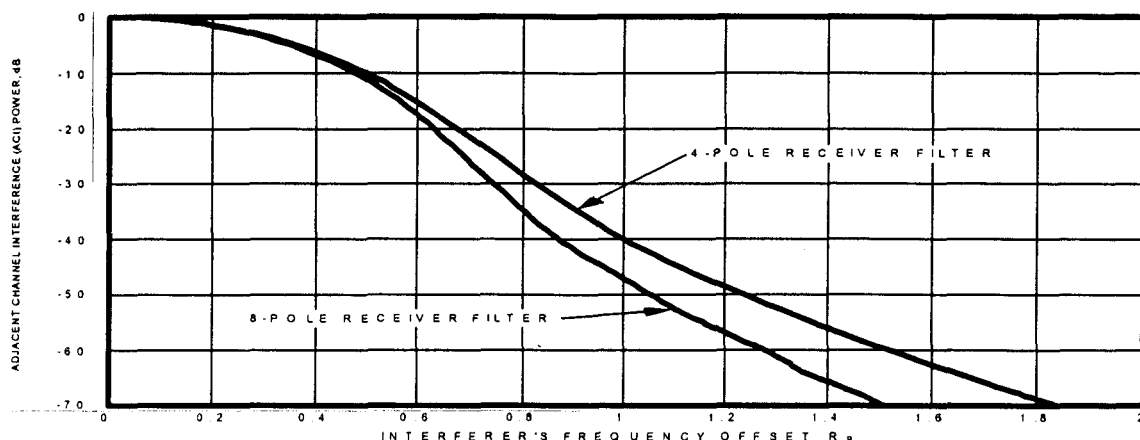


Figure 3.4-3: FQPSK-B Susceptibility to Adjacent Channel Interference (Theory)

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A more dramatic picture of interference immunity is shown in Figure 3.4-4. Bit-Error-Rate (BER) is plotted as a function of received signal power (E_B/N_0) for two FQPSK-B signals placed $1 R_B$ apart. Here, the interferer's signal power is 20 dB stronger than the victim's. Referring to the line representing a BER 1×10^{-3} , it can be seen that the victim suffers only about a 1.1 dB loss in a receiver having a 4-Pole filter and approximately a 0.9 dB loss if the receiver has an 8-Pole filter with a sharper roll-off. There is no doubt this is due to the very steep attenuation of the FQPSK-B spectrum.

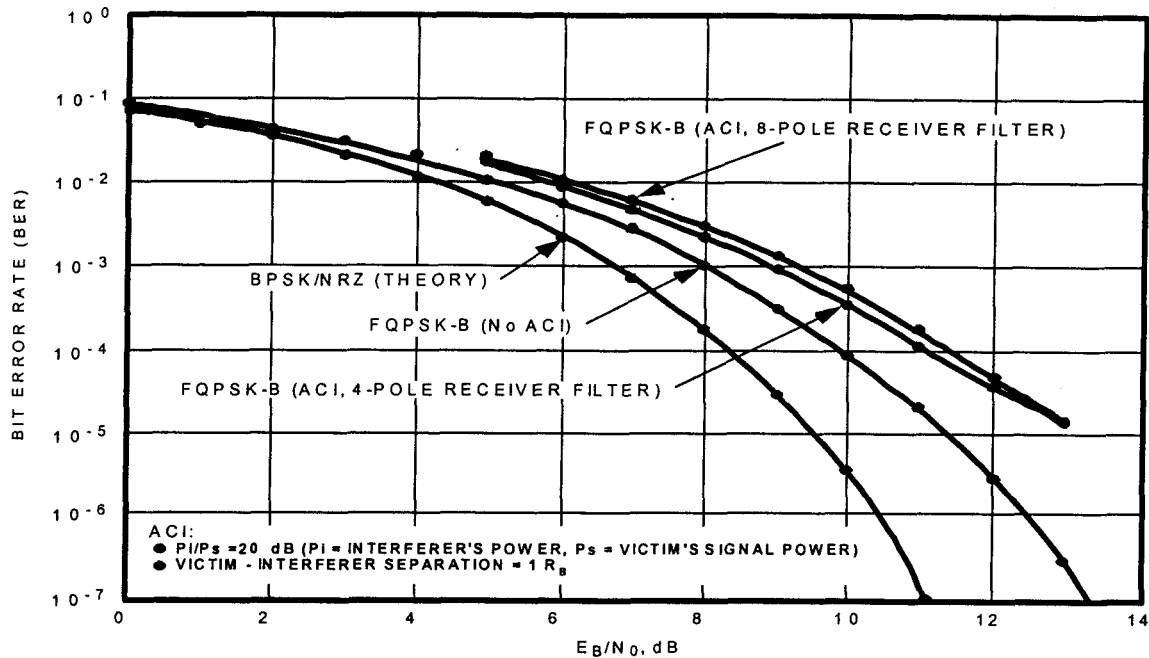


Figure 3.4-4: FQPSK-B Bit-Error-Rate Susceptibility to ACI (Theory)

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3.5 Spread Spectrum

Although not a part of the Workplan (see Section 1), a cursory look at spread spectrum communications is included in this Phase 4 report. It is included because some members of the SFCG speculated that the properties of spread spectrum modulation are superior to those of bandwidth limited modulation. One representative to SFCG-18 expressed the opinion that spread spectrum communications could actually be "more bandwidth efficient" than the modulation types studied by the CCSDS in their Phase 3 report.

The principal focus of this Phase 4 study is interference susceptibility; however, as noted in Section 3.3, this is but one consideration. The better question is: Which modulation type permits the maximum number of users in a frequency band having fixed edges while providing mutual interference immunity? The following information addresses some of these issues.

A Direct Sequence Spread Spectrum (DSSS) signal is generated by mixing a Pseudo Noise (PN) code with the data. In the receiver, the inverse process occurs when a local model of the PN code is cross-correlated with the received signal. After the local model's PN code phase is aligned with that in the received signal, the spread spectrum is de-convolved to that of the original data.

Theoretically, multiple spread spectrum signals can be overlain, provided that the PN codes are mutually orthogonal so that their cross-correlation is 0. Individual receivers perform the cross-correlation process described above with result that several channels can all occupy the same frequency spectrum.

A PN code's bit rate is termed the chip rate and the information data-to-chip rate ratio is an important parameter. Termed the *processing gain*, this parameter determines the amount of spectral spreading that occurs. Typical values lie between 100 and 1,000. The higher the processing gain, the better spread spectrum modulation works. DSSS binary phase shift keyed modulation's spectra will have the familiar $\text{Sin } x/x$ form with nulls at 1/chip period and lines spaced at 1/chip repetition period.

Assuming that spread spectrum transmissions must lie within the allocated frequency band and that filtering is employed to limit the transmitted spectrum to only the main lobe, maximum permitted symbol rates for a spread spectrum system can be computed using the relationship:

$$\text{Data Rate} = \frac{\text{Allocated Bandwidth}}{\text{Processing Gain}} \times \frac{2 \text{ for OQPSK}}{2 \text{ for sidebands}}$$

If a rate $\frac{1}{2}$ convolutional code is used, the information data rate will be reduced by half. Moreover, these values assume a single user is permitted to spread his signal over the entire 90 MHz bandwidth when operating in the 2 GHz band and over the entire 50 MHz bandwidth when in the 8 GHz band.

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When multiple spread spectrum channels are "stacked", signals with orthogonal cross-correlation properties appear as noise in other than the intended receivers. This has the effect of degrading the Signal-to-Noise-Ratio (SNR). The amount of degradation depends the spread spectrum signal's power spectral density and the victim receiver's system noise temperature and explains why larger processing gains are preferred. Accordingly, there is a limit to the number of spread spectrum signals that can overlay each other.

Fourth Finding:

As a practical matter for a processing gain of 1,023, about 300 Direct Sequence Spread Spectrum signals can overlay one another before the additive noise level in a victim receiver, operating at an 8 dB SNR, becomes excessive (Reference 5).

This comparatively small number appears to be inconsistent with the PCS industry's experience. But, there are two differences. First, cell phones have a comparatively low information data rate so that, even when their signals are spread, a single user's signal does not require the entire allocated band. Cell phone users can be stacked side-by-side as well as vertically. Second, spacial diversity makes it unlikely that more than the acceptable number of users will be attempting to reuse the same frequency in the same cell at the same time.

Figure 3.5-1 shows a DSSS system's BER as a function of received signal strength (E_B/N_0), in the presence of narrowband RFI, for three different processing gains: 31, 127, and 1023. The interferer is spaced $1 R_B$ from center frequency of the DSSS system and has equal power.

Two points are worth noting. First, a DSSS system's performance in the presence of narrowband interference is very much a function of its processing gain, the higher the better. Second, the figure suggests that a minimum processing gain of 100 is required unless larger losses from interference and fewer independent channels can be tolerated.

This finding is corroborated by Figure 3.5-2 which shows the degradation in E_B/N_0 as a function of separation between interferer and victim for wideband RFI. Degradation is independent of the separation (see explanation in Section 3.2) and is essentially 0 dB for a processing gain of 1023, 0.5 dB for a gain of 127, and 1.3 dB for a gain of 31. A curve for unfiltered, ideal BPSK is included for reference purposes and is equivalent to the 0 dB curve in Figure 3.1-2b.

Comparing Figure 3.5-1 with Figure 3.2-2b for SRRC filtered OQPSK, in the presence of a narrowband interferer having equal power, yields an interesting finding. For a narrowband interferer and a 1×10^{-3} BER, a DSSS system, with a processing gain of 127 or lower, will equal or exceed a 0.5 dB loss at any frequency separation between victim and interferer. A filtered OQPSK system is only susceptible when the narrowband interferer is within $0.5 R_B$.

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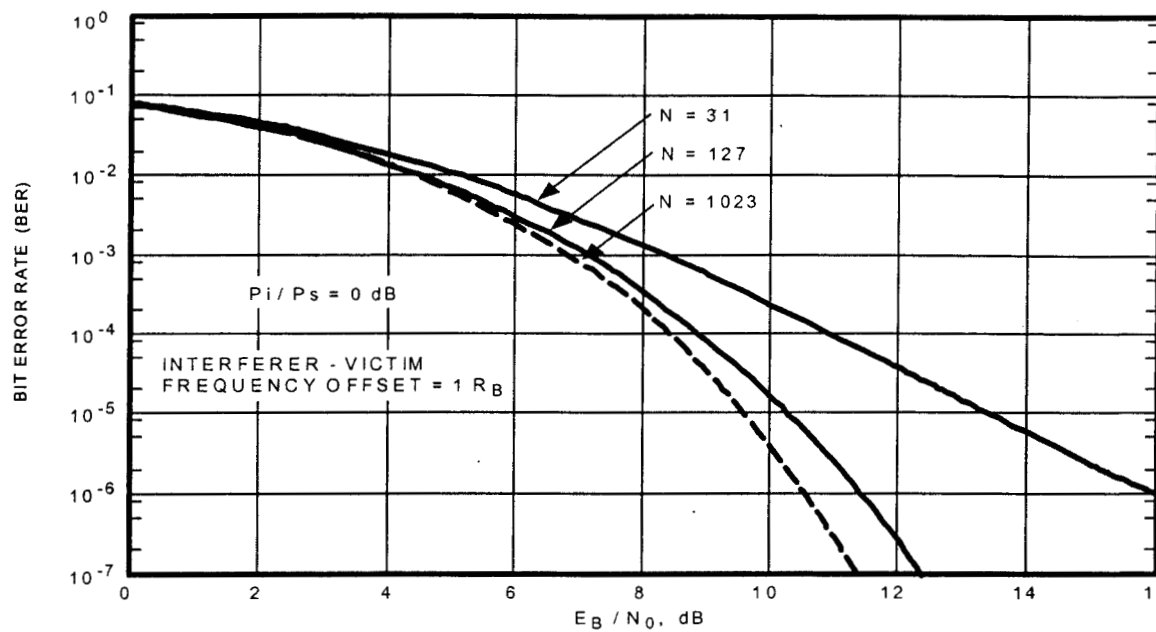


Figure 3.5-1: DSSS Bit-Error-Rate Susceptibility to Narrowband Interference

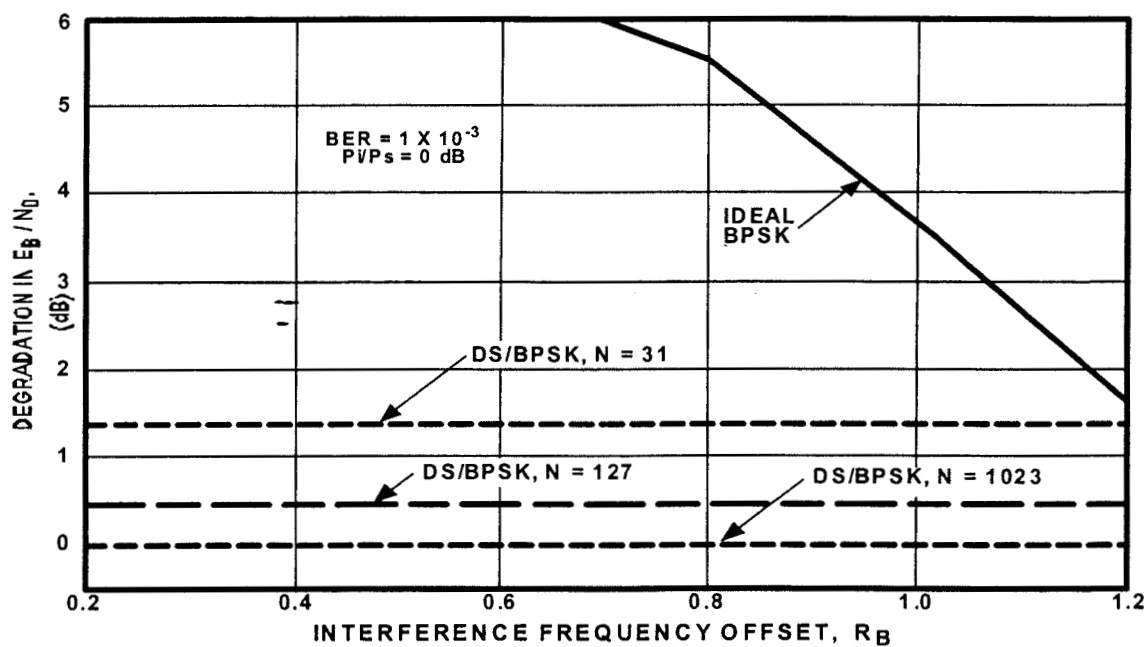


Figure 3.5-2: DSSS SNR Susceptibility to Wideband Interference

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3.5.1 DSSS Spectral Efficiency

The principal purpose behind the *Efficient Modulation Methods Study* was to identify those modulation methods permitting the maximum number of independent users to operate simultaneously in a specified bandwidth. Given the speculations put forth in SFCG-18, it would be interesting to compare DSSS systems with one of the more bandwidth efficient modulation schemes studied in Phase 3. This analysis of the two systems compares two parameters:

1. The maximum number of users that can simultaneously operate in a fixed bandwidth.
2. The maximum number of bits per second that be returned.

The study also includes the following assumptions:

1. Users operate in the Category A mission 2 GHz band allocated to the *Space Research* service.
2. Total spectral emissions must lie within the 90 MHz allocated band but may use entire band.
 - a) DSSS users must filter to transmit only main spectral lobe.
 - b) FQPSK-B users are packed side-by-side at $1 R_b$ with no additional filtering.
3. The maximum bit-rate for the DSSS system is given by:
$$\begin{aligned} &[(\text{Allocated Bandwidth} / \text{Processing Gain}) \times (2 \text{ for OQPSK} / 2 \text{ for sidebands})] \\ &= \text{Allocated Bandwidth} / \text{Processing Gain} \\ &= 708,661 \text{ bps for a processing gain of 127.} \\ &= 87,977 \text{ bps for a processing gain of 1023.} \end{aligned}$$
4. The maximum number of equal power DSSS users that can be "overlaid" is (Reference 6):
 - a) 37 for a Processing Gain of 127.
 - b) 75 for a Processing Gain of 255
 - c) 150 for a Processing Gain of 511
 - d) 300 for a Processing Gain of 1023.
5. Maximum number of simultaneous independent FQPSK-B users is given by:
$$\begin{aligned} &[(\text{Allocated Bandwidth} / \text{Data Rate}) \times (2 \text{ for OQPSK} / 2 \text{ for sidebands})] \\ &= \text{Allocated Bandwidth} / \text{Data Rate} \end{aligned}$$
6. Evaluations made at a $\text{BER} = 1 \times 10^{-3}$.
7. Adjacent channel interference shall not exceed 1 dB.

Study results for the 2 and 8 GHz bands *Space Research* (SR) and *Earth Exploration Satellite* (EES) services are summarized in Table 3.5-1. Several observations can be made:

1. DSSS systems are useable only at low data rates.
 - a) Maximum data rate of 709 kbps in 2 GHz *Space Research* service allocation.
 - b) Maximum data rate of 394 kbps in 8 GHz *Space Research* service allocation.
 - c) Maximum data rate of 2.95 Mbps in 8 GHz *EES* service allocation.
2. DSSS systems are not very bandwidth efficient. At a 1×10^{-3} BER, there can be nearly $3\frac{1}{2}$ times as many users in an allocated band if they use FQPSK-B rather than DSSS modulation.

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Table 3.5-1: Comparison of DSSS and FQPSK-B Channel Capacities for 2 GHz Band

Band (GHz)	ITU Allocated Service ¹	Allocated Bandwidth (MHz)	DSSS Processing Gain	Max. DSSS Data Rate (kbps)	Max. Simul. DSSS Users (No.) ²	Max. DSSS Band Cap. (Mbps)	Max No. FQPSK-B Users	Max. FQPSK-B Band Cap. (Mbps)	FQPSK/DSSS Band Cap Ratio
2	SR	90	127	709	37	26	127	90	3.4
2	SR	90	255	353	75	26	255	90	3.4
2	SR	90	512	176	150	26	512	90	3.4
2	SR	90	1023	88	300	26	1023	90	3.4
8	SR	50	127	394	37	15	127	50	3.4
8	SR	50	255	196	75	15	255	50	3.4
8	SR	50	512	98	150	15	512	50	3.4
8	SR	50	1023	49	300	15	1023	50	3.4
8	EES	375	127	2,953	37	109	127	375	3.4
8	EES	375	255	1,471	75	110	255	375	3.4
8	EES	375	512	732	150	110	512	375	3.4
8	EES	375	1023	367	300	110	1023	375	3.4

Notes:

1. SR = Space Research service; EES = Earth Exploration Satellite service.

2. Based on a 8 dB SNR; BER = 1 E-3 (Reference 7)

It is clear that DSSS systems may have application in spreading the spectrum to meet Power Flux Density (PFD) requirements, but only if bandwidth efficiency is not a top priority. Generally, PFD will only be a concern when residual carrier systems are used. SFCG Recommendation 17-2R1 requires users of data symbol rates above 2 Msps to use suppressed carrier modulation. Data rates typically found in suppressed carrier modulation systems are very unlikely to exceed PFD limits, even when they employ bandwidth efficient modulation methods.

Fifth Finding:

DSSS modulation is not appropriate for any space mission transmitting a telemetry data rate in excess of 2 Msps and which is covered by SFCG Recommendation 17-2R1.

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4.0 SUMMARY AND CONCLUSIONS

This study has examined the several modulation methods for their susceptibility to both narrowband and wideband interference as requested in the Workplan contained in Section 1. Pursuant to a request in the Workplan, narrowband and wideband interference susceptibilities were determined by analysis. Where possible, they were confirmed by hardware simulations or actual measurements. Table 4.0-1 summarizes the narrowband interference susceptibility for several losses from 0.25 to 1.0 dB. Table 4.0-2 provides the equivalent values for wideband interference.

Table 4.0-1: Data Degradation From Narrowband Interference of Equal Power (Theory)

Modulation Type	Minimum Interference Offset from f_c for Specified Data Loss ¹			
	0.25 dB Loss	0.50 dB Loss	0.75 dB Loss	1.00 dB Loss
Unfiltered BPSK-NRZ	$\pm 2.5 R_B$	$\pm 1.7 R_B$	$\pm 1.6 R_B$	$\pm 1.5 R_B$
OQPSK (BW, BT = 1)	$\pm 0.7 R_B$	$\pm 0.47 R_B$	$\pm 0.45 R_B$	$\pm 0.43 R_B$
OQPSK (SRRC, $\alpha = 0.5$)	$\pm 0.38 R_B$	$\pm 0.37 R_B$	$\pm 0.36 R_B$	$\pm 0.35 R_B$
GMSK ($BT_B = 0.50$)	$\pm 0.6 R_B$	$\pm 0.58 R_B$	$\pm 0.5 R_B$	$\pm 0.53 R_B$
GMSK ($BT_B = 0.25$)	$\pm 0.52 R_B$	$\pm 0.49 R_B$	$\pm 0.47 R_B$	$\pm 0.46 R_B$
FQPSK-B	$\pm 0.52 R_B$	$\pm 0.49 R_B$	$\pm 0.46 R_B$	$\pm 0.42 R_B$
Spread Spectrum	Never	Never	Never	Never

NOTE: 1. Based upon equal powers in interfering and desired signals.
2. Based on a Processing Gain of 1023.

Table 4.0-2: Data Degradation From Narrowband Interference of Equal Power (Theory)

Modulation Type	Minimum Interference Offset from f_c for Specified Data Loss ¹			
	0.25 dB Loss	0.50 dB Loss	0.75 dB Loss	1.00 dB Loss
Unfiltered BPSK-NRZ	$\pm >3 R_B$	$\pm 2.5 R_B$	$\pm 2.4 R_B$	$\pm 1.8 R_B$
OQPSK (BW, BT = 1)	$\pm 1.05 R_B$	$\pm 0.96 R_B$	$\pm 0.88 R_B$	$\pm 0.8 R_B$
OQPSK (SRRC, $\alpha = 0.5$) ²	$\pm 1.3 R_B$	$\pm 1.0 R_B$	$\pm 0.93 R_B$	$\pm 0.9 R_B$
GMSK ($BT_s = 1.0$)	$\pm 1.3 R_B$	$\pm 1.18 R_B$	$\pm 1.12 R_B$	$\pm 1.09 R_B$
GMSK ($BT_s = 0.5$)	$\pm 1.06 R_B$	$\pm 0.98 R_B$	$\pm 0.90 R_B$	$\pm 0.85 R_B$
FQPSK-B ²	$\pm 0.79 R_B$	$\pm 0.77 R_B$	$\pm 0.75 R_B$	$\pm 0.72 R_B$
Spread Spectrum ³	Never	Never	Never	Never

NOTE: 1. Based upon equal powers in interfering and desired signals.
2. Based on hardware simulation.
3. Based on a Processing Gain of 1023.

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Susceptibility of a victim receiver to narrowband interference of equal power is approximately the same for all filtered modulation types save SRRC ($\alpha = 0.5$) OQPSK (Table 4.0-1). OQPSK appears better for an interferer of equal power to the victim because OQPSK's main spectral lobe is somewhat narrower than either GMSK's or FQPSK's down to a level of 20 dB below the peak. Thereafter, it becomes much wider than either GMSK or FQPSK-B. Section 3.3 explains why this apparent advantage is not applicable to space science missions.

The susceptibility of filtered modulations to wideband interference also tends to be grouped with FQPSK-B being slightly better than the others. It remains to be demonstrated whether that advantage results from hardware simulations rather than a theoretical computation. A somewhat similar result was found for Butterworth ($BT = 1$) filtered OQPSK where it appears slightly better than SRRC ($\alpha = 0.5$) filtered OQPSK. It is likely that all are quite similar.

Spread spectrum modulation has virtual immunity to narrowband and wideband interference provided the processing gain is high (1023). At lower processing gains (31) the interference susceptibility of spread spectrum modulation to either narrowband or wideband interference increases sharply.

All filtered modulation types have less susceptibility to interference than does unfiltered BPSK. That disparity will become ever more evident as the interferer's power increases with respect to the victim's. Considering the space science applications described in Section 3.3 and Reference 4, approximately $3\frac{1}{2}$ times as many FQPSK-B (or GMSK) users can be packed into an allocated frequency band than is possible with either SRRC ($\alpha = 0.5$) OQPSK or DSSS modulation, without any concern about mutual interference Table 3.5-1).

Several other observations were made throughout the several sections of this report. They are repeated here for the convenience of the reader.

1. **Definition of Interference Susceptibility:** The likelihood that another signal source, operating in the same, or other, allocated frequency band, will produce an unacceptable degradation to a victim employing bandwidth efficient modulation.
2. The amount of the degradation to the desired data signal (S_D) is proportional to power remaining in the interfering signal (P_I), after attenuation by the receiver filter's roll-off characteristic, compared to the total power in the desired signal (P_{TS}). Specifically, $S_D \propto P_I / P_{TS}$.
3. Absent low noise and/or i.f. amplifier saturation or gain compression resulting from an interfering signal, a receiver's performance in the presence of an interfering signal is determined entirely by its filters.

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5. To minimize interference susceptibility, a matched filter's bandwidth should be as narrow as possible after accounting for the minimum acceptable power transfer, and the maximum acceptable ISI.
6. When comparing interference susceptibility of different modulation methods, those with more compact spectra (smaller necessary bandwidths) have more interference immunity than modulation types requiring larger bandwidths, provided that the receiver has a properly matched filter.
7. The power spectral density of a bandwidth efficient modulated signal is increased with respect to a non-baseband filtered modulation, reducing its susceptibility to a narrowband interferer having the same total transmitting power.
8. If the receiver has a properly designed matched filter, there will be virtually no susceptibility to interference lying outside its bandwidth. Therefore, a narrowband interferer, occurring within the victim's allocated frequency band, has a lower probability of falling within the victim's narrower bandwidth.
9. For equally received power from interferer and victim, SRRC ($\alpha = 0.5$) OQPSK permits slightly tighter user packing; however, when distances vary so that the received powers are unequal such as is found in space applications, then about $3\frac{1}{2}$ times more GMSK and/or FQPSK-B users can be placed in a band than is possible with OQPSK modulation.
10. As a practical matter for a processing gain of 1,023, about 300 Direct Sequence Spread Spectrum signals can overlay one another before the additive noise level in a victim receiver, operating at an 8 dB SNR, becomes excessive (Reference 5).
11. DSSS systems are not very user efficient. At a 1×10^{-3} BER, there can be nearly $3\frac{1}{2}$ times as many users in an allocated band if they use FQPSK-B rather than DSSS modulation.
12. DSSS systems are not very bandwidth efficient. At a 1×10^{-3} BER, an FQPSK-B system can move nearly $3\frac{1}{2}$ times more bits in a fixed bandwidth per unit time than can a DSSS system.
13. DSSS modulation is not appropriate for any space mission transmitting a telemetry data rate in excess of 2 Msp, which must operate in the 2 and 8 GHz *Space Research* or *Earth Exploration Satellite* services and which is covered by SFCG Recommendation 17-2R1.

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GLOSSARY

BER	Bit-Error-Rate
BPSK	Binary Phase Shift Keyed
BT	Bandwidth-Time (factor specifying filter bandwidth)
CCSDS	Consultative Committee for Space Data Systems
DSN	Deep Space Network
DSP	Digital Signal Processor
DSSS	Direct Sequence Spread Spectrum (modulation)
ESA	European Space Agency
ESOC	European Space Agency Center
f_c	Center (or Carrier) Frequency
FIR	Finite Impulse Response (filter mechanization)
FQPSK	Feher Quadrature Phase Shift Keyed (modulation method)
FQPSK-B	A Special Configuration of FQPSK
GMSK	Gaussian Minimum Shift Keyed
GSFC	Goddard Space Flight Center
HDL	Hardware Description Language
I-Q	In-Phase-Quadrature (modulator mechanization)
ISI	Inter-Symbol Interference
JPL	Jet propulsion Laboratory
ksp/s	Kilo-symbols per second (1×10^3 symbols per second)
Msp/s	Mega-symbols per second (1×10^6 symbols per second)
QPSK	Quadrature Phase Shift Keyed
OQPSK	Offset QPSK ($\frac{1}{2}$ -bit-time offset)
PCS	Personal Communications System
PFD	Power Flux Density
P_i/P_s	Ratio of Interferer's Total Transmitted Power to Victim's Total Transmitted Power
PSD	Power Spectral Density
NASA	National Aeronautics and Space Administration
NRZ	Non Return to Zero
R_B	Frequency Span Corresponding to 1/Data-Bit Period
RFI	Radio Frequency Interference
SFCG	Space Frequency Coordination Group
SRRC	Square Root Raised Cosine [filter]
SSPA	Solid State Power Amplifier
TDL	Telemetry Development Laboratory (located at JPL)

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